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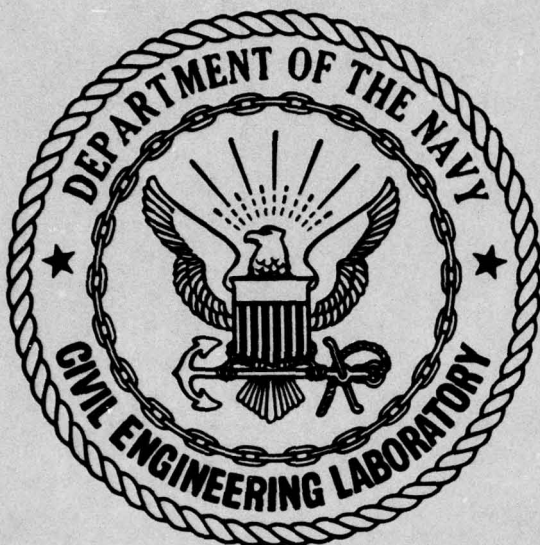
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CIVIL ENGINEERING LABORATORY
Naval Construction Battalion Center
Port Hueneme, California

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PLACEMENT OF CONCRETE IN THE OCEAN

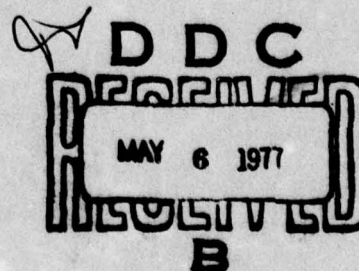
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An Investigation Conducted by

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| → This report presents state-of-the-art and proposed methods of concrete placement in the ocean to depths of 20,000 feet. Current technology includes bucket, tremie pipe, pumping, preplaced aggregate and bagged concrete methods as well as oil field cementing techniques. Problem areas, limitations and deficiencies of the current technology and discussed. → next page | | |

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ABSTRACT

This report includes a state-of-the-art study on concrete placement in the ocean. Current technology includes concrete placement by bucket, tremie pipe and pumping, as well as preplaced aggregate and bagged concrete methods. Concrete pumping technology is confined to horizontal and upward movements primarily, but a treatise is given on pumped cement slurry methods now used in oil field grouting techniques. Problem areas are pointed out, along with the limitations and deficiencies of the current technology.

Five new concepts of ocean concrete placement are presented and evaluated, most of which are variations of the current tremie method or bucket placement. Eight recommendations for future research efforts are made. These recommendations include research on materials and their properties, test methods, control devices and guidance systems for placement. A comprehensive bibliography is also included.

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PLACEMENT OF CONCRETE IN THE OCEAN

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1. INTRODUCTION

The study for placement of concrete in the ocean is to identify and describe methods, materials and equipment to place or cast concrete on the seafloor at deep ocean depths. Placement is accomplished by moving the concrete from the mixer on the surface to a position on the ocean floor by gravity flow, pumping or any other known method. Primary interest is in the placement of small volumes (several hundred cubic yards) and large volumes (several thousand cubic yards) of concrete at depths of 1,000 feet and 20,000 feet.

Underwater concrete placement utilizing poured concrete mixtures has been attempted since about 1910. The usage has increased since the early 1940's when it was used to build dry docks, bridge piers, and underwater foundations. Underwater placement techniques have improved during these ensuing years, with the biggest incentive being provided by offshore oil drilling and government construction of underwater facilities. Until the late 1960's and early 1970's, the deepest water in which concrete mixes had been placed was less than 200 feet. The depth of concrete placement has slowly increased as methods and techniques have been improved. Methods used to date are:

1. Bucket placement method.
2. Tremie method.
3. Pumped concrete method.
4. Pumped cement slurry method.
5. Preplaced aggregate method
6. Bagged concrete method.

The purpose of this report is to present a state-of-the-art of concrete placement in the ocean, and to discuss the problems, limitations and deficiencies of present techniques. Oil field techniques using pumped cement slurries will also be included. Five new concepts of placement will be presented and recommendations made for further research efforts.

2. EXISTING STATE-OF-THE-ART FOR TECHNOLOGY APPLICABLE TO CONCRETE PLACEMENT

A. Current Underwater Placement Methods

The placement of concrete mixtures under water has been accomplished by all six methods listed, primarily at depths less than 500 feet, using volumes ranging from 7 cubic yards to thousands of cubic yards, as shown in Table 1. The smallest volumes are by bucket placement, primarily to seal caissons or forms prior to dewatering for subsequent concrete placement. The depths shown reflect primarily the depths at which the concrete placement has been diver controlled or monitored, and where containment of the concrete was controlled by trenches, holes, forms, pipe or bags. The placement of concrete in a confined space under water, such as a form, usually required placing of excess concrete to allow for wastage of concrete that was in contact with the water. If the placed concrete was required to have a finished elevation, subsequent finishing work would be necessary to assure competent concrete on the exposed surface.

(1) Bucket Placement Method

Bucket placement of concrete materials is the process whereby concrete materials are transported from the surface to the point of placement in individual containers. The containers are of a geometric shape, usually with a discharge valve on the bottom of the container. The containers are normally covered for underwater placement of concrete materials, with the cover containing a vent or a flexible cover that can displace the concrete from the bucket. The buckets are usually hoisted by cables or chains and guided by rails or cables.

The placement of concrete mixture by buckets has been used for over 50 years. The use of buckets for placement of concrete requires the bucket to land on top of each preceding pour with the discharge under the surface of the in-place concrete. This is accomplished by partial submergence of the bucket or use of an extension pipe. The bucket placement is used in the construction of quay walls, caissons, etc., where buckets can be embedded in the previously placed concrete.

When the concrete mixes with the sea water, it forms a light coat of a frothy cream or paste called laitance. If the subsequent flow of concrete stays beneath this surface, the laitance just rises to the top where it can be overflowed or jetted off. Obstructions, interruptions, or agitation all tend to disturb the surface and cause greater amounts of laitance. The bucket method of placement produces and traps more laitance than other methods of placement.

A satisfactory bucket-placed mixture has a 5- to 6-inch slump, and contains 6 to 7 sacks of cement, 1-1/2 to 2-inch aggregate, and a sand content of 40% or more.^{1*} Stiffer or drier mixtures, having a 2- to 3-inch slump, can be placed by buckets when concrete is placed in moving water or surf zones where there is not adequate protection from side or top forms.

* Superscript numbers refer to references listed in Chapter 5.

TABLE 1

PLACEMENT OF CONCRETE IN THE OCEAN

| Placement Method | Quantities Placed | Rate | Water Depth (Deepest) | Sea Condition | Remarks |
|----------------------|--|---|---|---------------|---|
| Bucket | Small | .25-5.25 cu yd/ trip | 400 feet or diver working depth | Max. 5 feet | |
| Tremie | 100-150 cu yd/ pipe, depending on set time of mix | 36-66 cu yd/hr | 170 feet | Max. 5 feet | |
| Pumped Concrete | 1,300,000 cu yd | 32.7 cu yd/hr | 1,000 feet | | Displaced fluid from a cavern under a dam |
| Pumped Cement Slurry | 580 cu yd 4,136 cu yd 2,200 cu yd 7 cu yd | 96 cu yd/hr 200+ cu yd/hr 7.2 cu yd/hr — | 340 feet 5,010 feet 926 feet 11,753 feet | Max. 5 feet | Cement placed in drilled holes such as well and mine shafts |
| Preplaced Aggregate | Small | 30-40 cu yd/hr | 300 feet | Max. 5 feet | |
| Bagged Concrete | Up to several hundred cubic yards | 9-65 cu yd/hr | 200-300 feet | | |

The bucket placement of concrete is limited in depth only by the hoisting equipment available, the setting time of the concrete, and the ability to guide the bucket to the placement point.² This method would be used primarily for small quantities (several hundred yards) at depths to about 400 feet. However, improvements in diving techniques have permitted divers to work down to 1,000 feet or more with the use of saturation diving techniques and equipment.³ If bucket placement is attempted without the assistance of divers, some methods would be required for determining the position of the bucket at the ocean floor when dumping the concrete. If used in deeper depths, the intermittent dumping could cause bridging in reinforcing steel and possibly cold joints in the concrete.

For over 50 years, bucket placement of oil well cement has been accomplished in wells at depths of several thousand feet, the depth being limited only by the hoist ability to handle the weight of the bucket, cement, and hoist line. Oil well cements have been placed in oil wells by the bucket (dump bailer) method at depths over 10,000 feet. These dump bailers are about 3 to 5 inches in diameter and will hold up to 1/2 cubic yard of cement slurry. Placed material is more subject to weakening by cold joints than methods that place concrete continuously.

(2) Tremie Placement Method

Tremie placement of concrete has been used to place concrete under water at depths approaching 200 feet by gravity flow of the concrete out of the tremie pipe. The placement of concrete by the tremie method is accomplished through a long pipe with a concrete receiving funnel on the top of the pipe, as shown in the four progressive views of Figure 1.

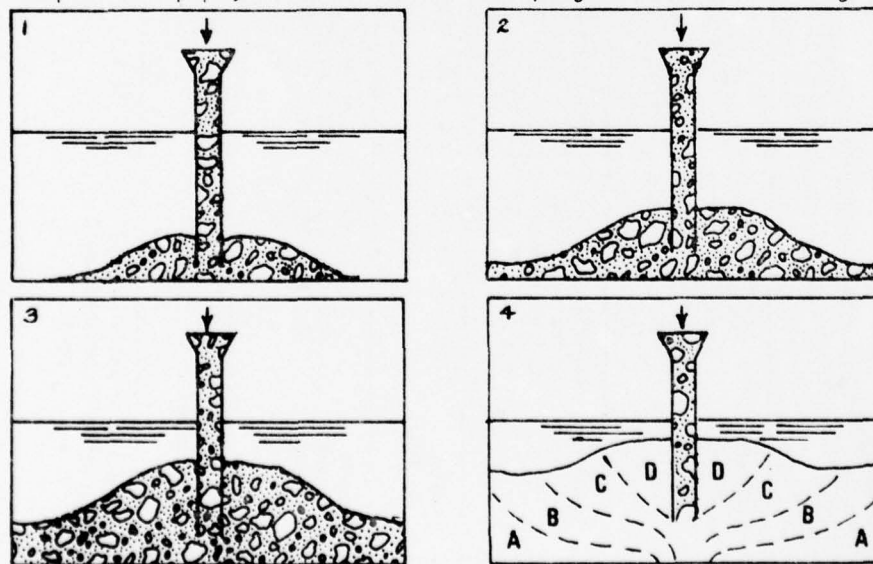


Figure 1. Tremie Concrete Placement

The end of the tremie pipe is set on bottom with the end of the pipe closed until the pipe is filled with concrete. When the tremie pipe is filled with concrete, the pipe is raised off bottom and the closure opened to permit the flow of concrete out of the pipe. The pipe must remain submerged in the concrete discharged from the pipe to control the flow and to keep the formation of laitance to a minimum at the water-cement interface. As the height of the placed concrete increases, the tremie pipe must be raised proportionately, but the end of the pipe must be kept submerged in the concrete.

Concrete placement by tremie has been limited to depths where the pressure head differential (40 to 60 foot head) between the concrete and water is small enough to give smooth placement and prevent the sudden emptying of the tremie pipe which might result in high velocity scouring of placed cement. Placement down to 170 feet has been made. Quantities placed have been small, e.g., several hundred cubic yards.

A two-string method for tremie filling, shown in Figure 2, has been developed where a smaller concrete supply pipe is run to an intermediate depth in the tremie pipe to supply concrete under atmospheric pressure only without entrapping air in the concrete. This also reduces the fluid head at the discharge of the tremie pipe.¹

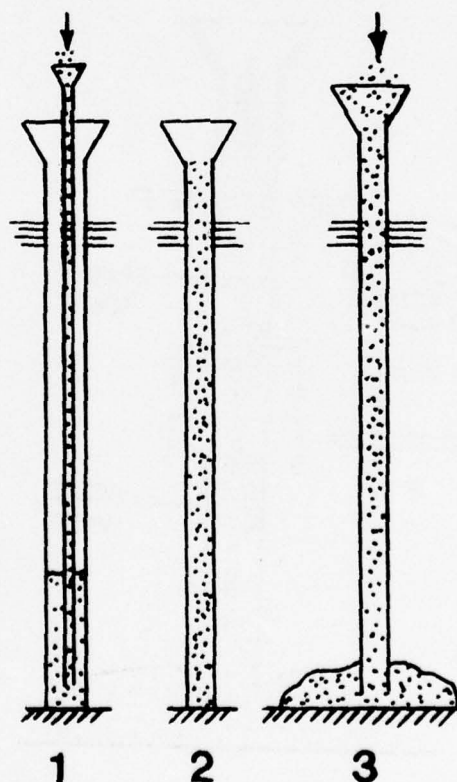


Figure 2. Two-String Method of Tremie Placement

A typical tremie concrete mixture would be as follows:

Cement - 7-8 sks/cu yd ASTM Type II

Coarse Aggregate - 3/4-inch maximum gravel

Sand - 33-38% of aggregate weight

Admixture - water reducing and retarding type,
2 oz per sack of cement

Water - enough to give a 6 to 8-inch slump
yet keep the water/cement ratio
below 0.45.

Variations in placement methods have been used to reduce the hydrostatic pressure differential between the concrete and water. One method has used a flexible tremie pipe that permits the pipe to be collapsed flat by external water pressure where concrete mix is not in the tremie pipe, as shown in Figure 3. The collapsible pipe allows concrete to be fed through the tremie pipe in intermittent batches, or slugs, thus keeping a relatively small length of concrete-filled pipe at the point of discharge. This has been used successfully in shallow applications only.

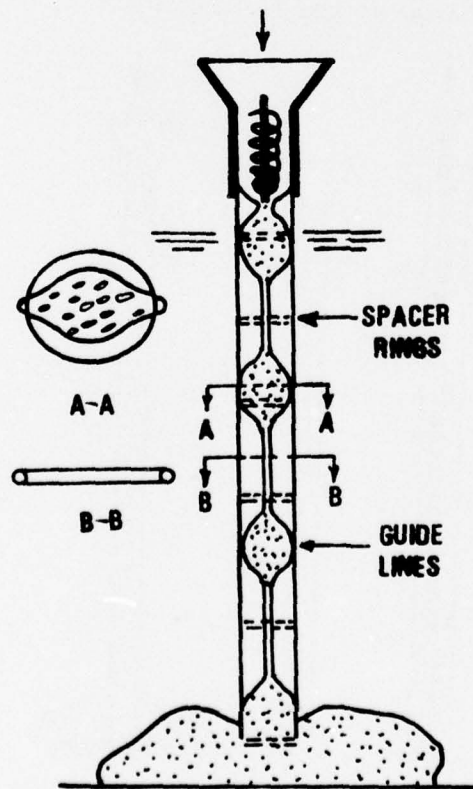


Figure 3. Flexible Collapsible Tremie Pipe

Some research work has been published on the placement of concrete under water by the tremie method to define the problems of laitance formation, flow patterns of cement placement and concrete bond characteristics.⁴ This work indicates that movement of the tremie pipe (or the use of additional pipes) is required to fill forms where the distance from the tremie to the form is greater than 15 feet.

(3) Pumped Concrete Methods

The placement of concrete by pumping through horizontal and vertical lines has been used successfully for many years in construction of buildings.⁵ Concrete has also been pumped downward through pipes into mines as deep as 1,760 meters (5,800 feet).⁶ Downward pumping is much more difficult because the concrete tends to separate as it falls and leave gaps in the column of concrete. The technique calls for such steps as the use of smaller aggregate and the use of mechanical aids to help control the fall of the concrete.

The concrete must have good lubricating qualities to be pumpable. A concrete with good workability is usually pumpable. Good pumpability is synonymous with low friction pressure and flowability.⁷ The concrete mixture should contain a portland cement, sand, aggregate and water. The water/cement ratio (lbs of water/lbs of cement) should not in general exceed 0.55. The minimum cement content should be 420 pounds per cubic yard of concrete. Natural, well-graded sand gives the best pumpability. Sand should have a fineness modulus (ASTM C 125) of 2.3 to 3.0; and grading should be near the center of ASTM C 33 limits, with 3-5% passing U.S. No. 100 sieve and 15-20% passing U.S. No. 50 sieve.

The grout of cement and fine sand is the primary source of lubrication, and there should be sufficient grout (at least 600 pounds) in each cubic yard of concrete to provide proper lubrication and aid in water retention. The aggregate should be well graded up to maximum size of about 1-1/2". The gradation should meet ASTM C 33 requirements and be as close to the middle range as possible.⁸ It is preferable for the shape of the aggregate to be as round as possible for ease of pumping. The minimum slump of the concrete should be 2 inches.

Materials which can be used to improve pumpability are as follows:

- (a) Cal Seal (Gypsum Cement) - 5 to 15% by weight of cement can be added to the portland cement.
- (b) Fly Ash - replaces 5-50% of the cement.
- (c) Fine Sand or Silica (U.S. No. 80 Sieve or Smaller) - 5-20% of sand.
- (d) Bentonite (or Attapulgate) - used in lieu of fine sand in amount of 1-5% by weight of cement.
- (e) Diatomaceous Earth - used in amount of 1-8% by weight of cement.
- (f) Pumping Aid Admixtures - high molecular weight polymers which add a measure of viscoelasticity to the water phase of concrete. Normal usage is 0.25 lbs/cubic yard.

For placement under water, 7 sacks of cement per cubic yard are recommended.⁹ The amount of coarse aggregate should be 1-1/2 to 2 times that of the fine aggregate. The slump can range from 4 to 7 inches.

There is a wide range of concrete pumps available on the market. These pumps can handle all kinds of mixes, and are capable of delivering up to 125 cubic yards per hour. Pumping distances range from 250 to 2,000 feet horizontally and from 75 to 400 feet vertically. The pumps can be purchased from about 20 major manufacturing firms - mounted on trucks, trailers or skids.¹⁰ Three types of pumps are available: piston, pneumatic and squeeze type.

The piston pump valves open and close, enabling concrete drawn from a hopper to be piston-driven from a chamber through a line. These pumps can be operated either hydraulically or mechanically. The pneumatic pumps use air pressure to force concrete from a chamber-hopper through the line. The squeeze type pump uses rollers rotating on a concrete-filled flexible tube to press the concrete forward in the pipeline. Additional concrete is brought into the tube by a vacuum acting on the outside of the flexible tube in the pump housing.

Common sizes for the discharge lines on the pumps range from 3 inches to 8 inches in diameter. The line sizes should be at least 2-1/2 times the largest aggregate diameter in the concrete pumped.

Placement of pumped concrete was used to fill a large, water-filled cavern under a dam in Turkey. The volume placed exceeded 1,000,000 cubic meters (1,308,000 cubic yards) at a depth of 305 meters (1,000 feet). The concrete batch plant that was used for dam construction was utilized to mix the concrete. Low placement rates were used due to the distance the concrete was pumped from the batch plant to the tremie pipe. The placement system consisted of 8-inch pipe grouted in the ground down to the cavern, with an inside 4-inch pipe used to place the concrete, as shown on Figure 4. Because of the large volume of concrete placed and the distance pumped, maximum aggregate size was 3/8-inch. Maximum placement rates were approximately 25 cubic meters/hr (32.7 cubic yards/hr) using a two-cylinder, hydraulically driven concrete pump. The 4-inch placement pipe was cleaned every two hours by pumping a plug or pig through the pipe and discharging the plug into the placed concrete. The closed vertical pipe system was necessary to control the cement placement rate.

This method could be used for small or large quantities placed at 1,000-foot depths and possible even to deeper depths.

A variation of the pumped concrete method is Intrusion-Prepack's bag method, where bags of suitable material, such as jute or coarsely woven cloth, are placed at the desired location underwater and retained in place with wire mesh, then filled with concrete, as shown in Figure 5.²

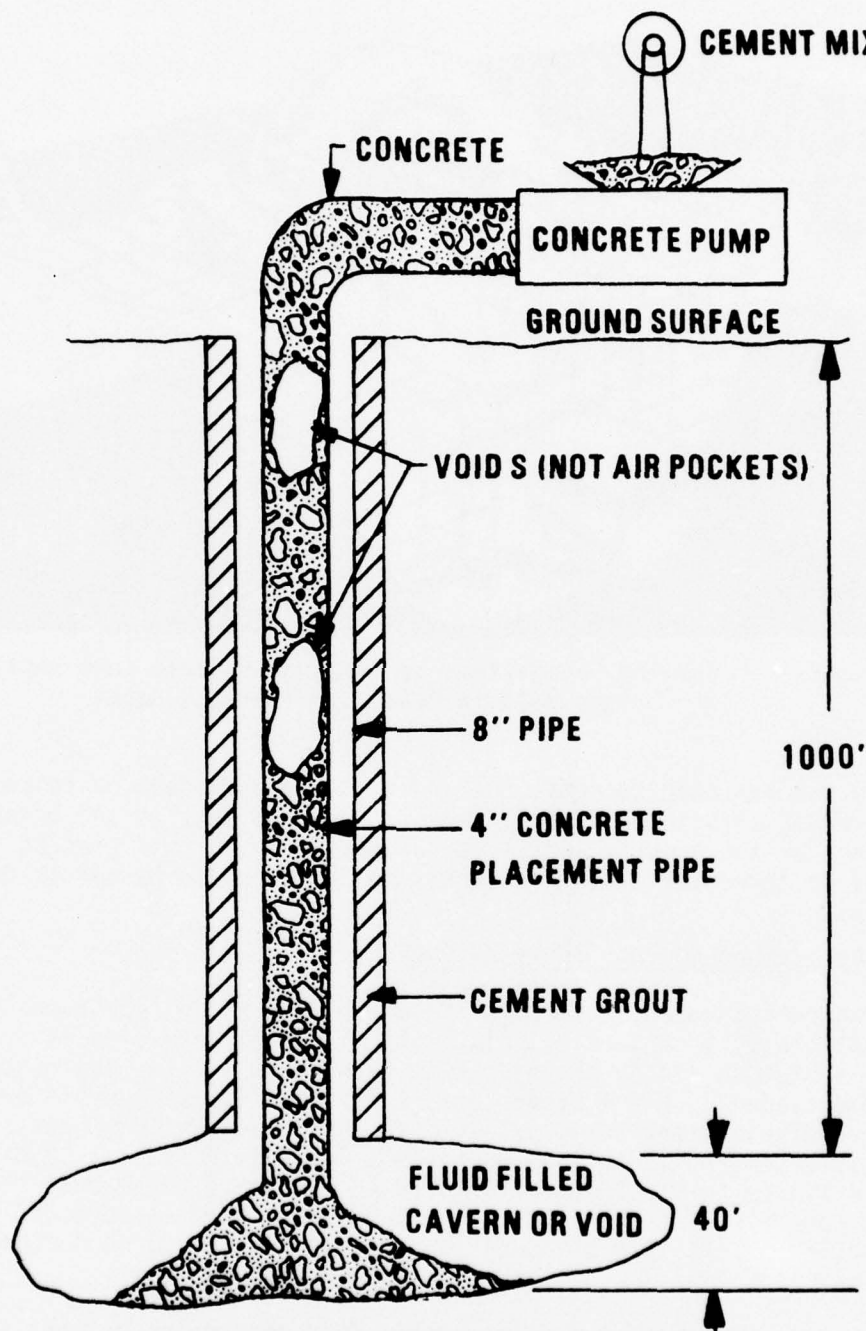


Figure 4. Pumped Concrete Placement at 1,000 Ft. Depth

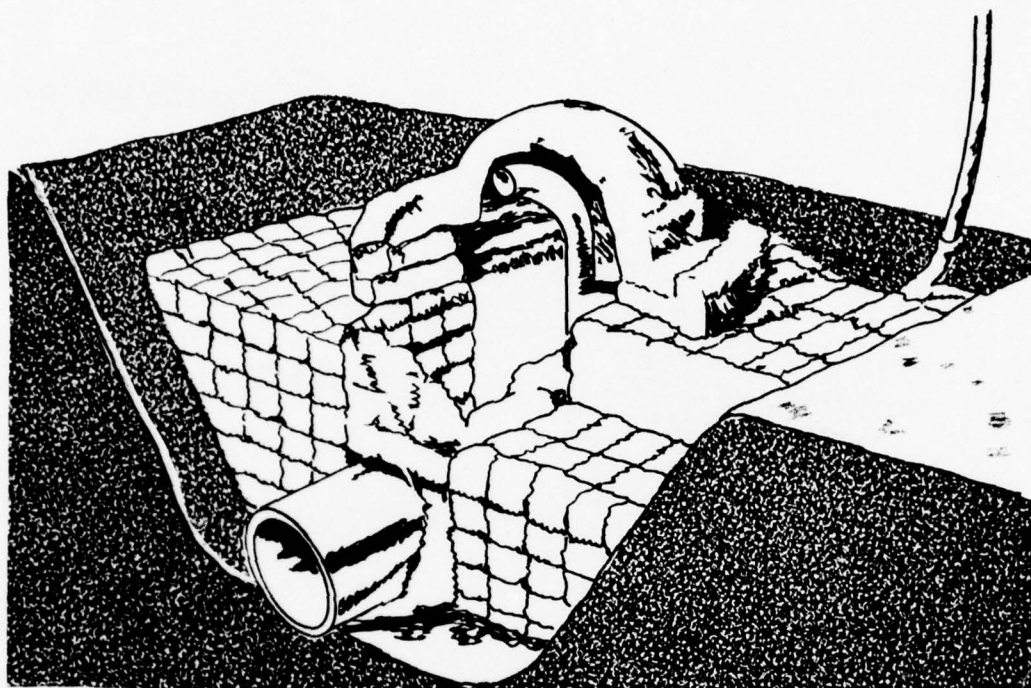


Figure 5. Forming Foundations by Pumping Concrete into Empty Bags Held in Place by Wire Mesh Cages

Primary use has been to construct underwater foundations or in the repair of submerged structures such as outfalls, piers, jetties and breakwaters. Placement of the bags is usually done by divers, so this process is limited by the diver placement technique, which would be depths down to 500 feet.

(4) Pumped Cement Slurry Method

Another placement method is the use of oil field type pumps to supply a cement slurry to a vertical placement pipe, which results in a closed supply system to aid in the placement of materials. The aggregates used do not exceed U.S. No. 4 sieve in size in order to be pumpable by these positive displacement pumps. This method of placement has been used in oil well cementing (grouting) operations for over 60 years. Additional information on this method is included in Section B. The bell-shaped foundations for offshore rigs shown in Figure 6 were constructed with this method. This type of operation has been performed to depths of 340 feet.^{11,12,13}

The use of a positive displacement pump to supply the vertical placement pipe provides a closed system that gives a higher degree of control of the placement rate by restricting the free fall of the cement slurry. Control of the placement rate without the intrusion of atmospheric pressure permits the placement of cement slurry at very deep depths in

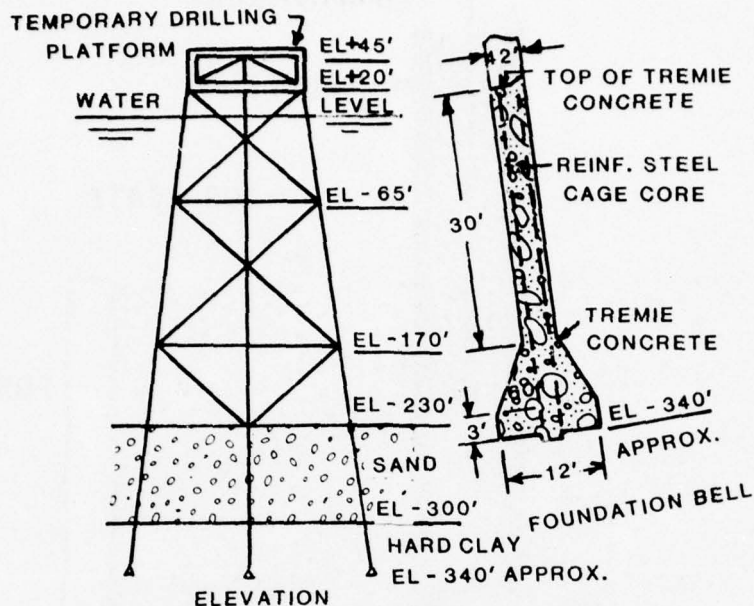


Figure 6. Tremie-Concrete Foundations for Offshore Platforms

large quantities (several thousand cubic yards). This method has been used in oil well cementing at depths exceeding 30,000 feet. A cement plug was set in a hole 472 feet deep through 5-inch drill pipe by the Glomar Challenger using this method in 11,750 feet of water.¹⁴

(5) Preplaced Aggregate Method

This method involves placing aggregate in a form and then pumping cement slurry into the aggregate to form concrete. The grout pipes should be extended into the forms, then coarse aggregate placed in the form. Grout (cement slurry) is then pumped into the aggregate through the grout pipes to fill the voids throughout the aggregate, as shown in Figure 7. The placement of the grout is usually at very low rates to prevent possible bypassing or channeling through the aggregate and placing pressure on the form.

There is no inherent limit to the depths at which the grout can be placed. The depth limit would be governed by the placement depth of forms and gravel. Actual depths of use have been up to 300 feet. The grout is a slurry mix of portland cement, sand and water, with admixture for improved pumping. This would be limited to small quantities of concrete placement at relatively shallow depths.

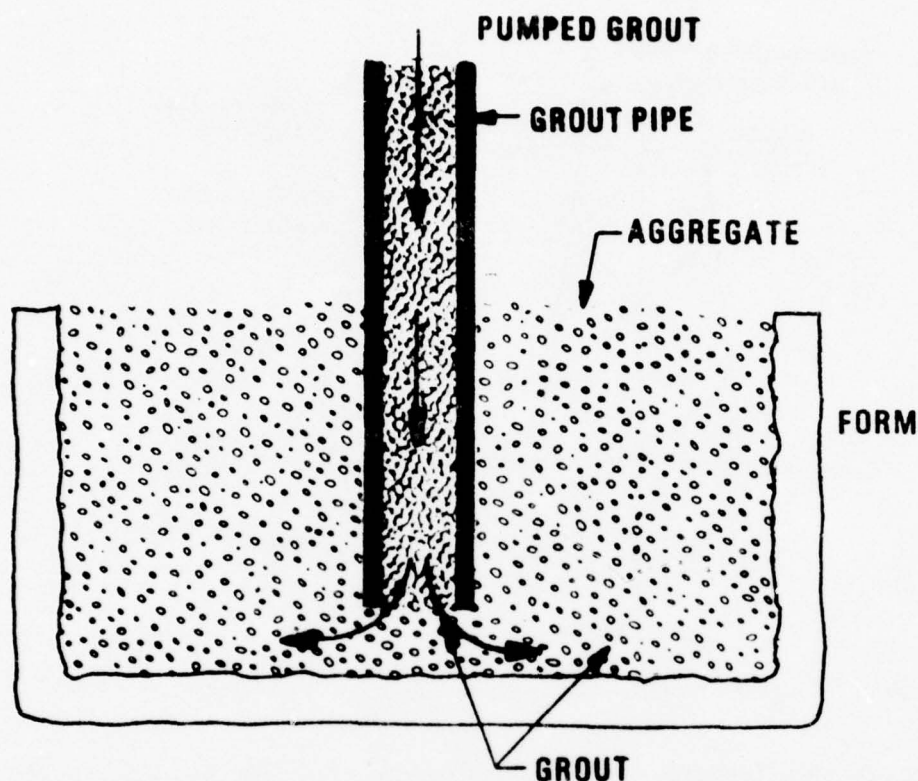


Figure 7. Schematic of Preplaced Aggregate Method

(6) Bagged Concrete Method

Bags filled with concrete mixtures have been successfully placed under water for the construction of structures. The bags are utilized with two types of mixtures, viz, dry concrete mixtures and wet concrete mixtures. The bags containing dry mixtures are of open weave construction to allow water to come in contact with the cement so that the concrete sets up in the bag. This also allows cement to seep from the bags to produce a solidified mass. Wet concrete mixtures are in large impermeable bags and do not require contact with the surrounding water in order to set. An alternate method is the filling of large bags (anchored to the ocean floor) with cement slurry to act as pipe spacers or supports.

Bag placement is normally accomplished by divers placing the bags in the required positions to construct the desired structure, such as retaining walls and seals around outfall pipes. Placement depths are from shallow depths to diver working depth of 200 to 300 feet. A similar method is being used in Mexico to construct retaining walls in surf zones to prevent beach erosion, and to construct walls in river mouths to prevent excessive silting of boat channels.

This method is not widely used, and would be applicable to small quantities at shallow depths.

B. Placement of Cement Slurry by Oilfield Techniques

(1) General

Oil well cementing is the process of pumping a cement slurry down the casing and up the annular space behind the pipe, where it is allowed to set. This acts as a sealant to help (a) protect the casing from external pressure that could collapse it, and (b) protect the casing from possible corrosion and electrolysis caused by formation waters or contact with various strata.

The first verified use of portland cement to shut off water in an oil well was in 1903. Since that time, vast improvements have been made in techniques, tools and materials to cope with problems encountered as wells were drilled deeper. Placement of cement slurries at depths in excess of 20,000 feet has been successfully performed many times. The experience gained by cementing of oil wells can possibly be utilized in placing some type of cement slurry on the ocean floor.

There is a great temperature differential between the bottom of wells and the ocean floor. Temperatures of 260°F or higher are normally encountered in wells below 12,000 to 15,000 feet. The ocean temperature drops to about 39°F at relatively shallow depths, then remains at this temperature even down into deep sections.

A wide variation of chemical additives are available to retard, accelerate, densify or lighten cement slurries. These will be discussed in a materials section. Equipment and techniques used in placing the cement will be discussed in other sections.

(2) Materials

The basic material for an oil well cement slurry is portland cement. The cement classification developed by American Society for Testing Materials (ASTM Specification C 150) covers five types of portland cements, primarily for construction usage. Type I is usually called "common" cement and is generally the cement used in construction. Type III is a "high early" cement, i.e., one which is used when a high early strength is desired. These two types are used in cementing oil wells. Types IV and V are not commonly used.

When deeper wells were drilled, it became apparent that the ASTM classification for cement would not meet the conditions encountered; therefore, a specification for oil well cement (API RP 10B) was formulated by the American Petroleum Institute. These cements are designated as Classes A, B, C, D, E, and F. Class A is similar to ASTM Type I and is the most widely used. Class C is a high early cement similar to ASTM Type III and is available in regular or high sulfate resistant types.

Classes D, E, and F are intended for wells with high temperature and pressures. Classes G and H have now been added. These are moderate sulfate resistant, low C_3A cements with a consistent grind which can be mixed very dense.

The oil activity in the Northern areas of Canada and Alaska have focused attention on the use of cement in low temperature applications. Much test work has been done on cementing compositions at low curing temperatures. It was found that this curing temperature is a significant factor in strength development.¹⁵ Figure 8 is a graph showing the curing time for several cements to reach a strength of 500 psi. At 40°F, which is the approximate temperature of the ocean floor, the time varies from 18 hours to 28 hours.

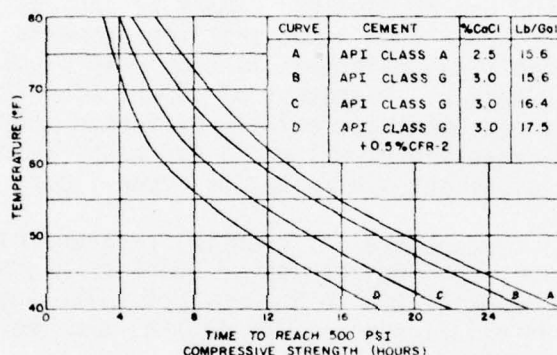


Figure 8. Curing Time to Reach 500 psi Compressive Strength

Most of the cement slurries now used in oil well cementing are special blends to meet specific well conditions. This is made possible by the wide use of additives which are available for cement alteration. Table 2 shows a cementing composition check list for materials which can be added to various classes of cement to accelerate or retard the slurry, increase or decrease the density, give low fluid loss, reduce friction and combat lost circulation. Because of the possibility of producing a "tailor-made" cementing composition, the conditions of the placement area can dictate the cement components for any particular job. It appears to be both possible and practical to mix a cement slurry which would set to a desired strength on the ocean floor, and to place that cementitious material in the desired location through a pipe from the ocean surface. Figure 9 shows the 28-day compressive strength at 75°F for seven slurries used in oil well cementing. Values are given for different densities of each slurry. The amount of admixture and the cement/water ratio is varied for each slurry to give 10 units of consistency (U_c). A unit of consistency is a standard value of measurement relating torque equivalent to degree of firmness of the cement slurry.

Table 2

CEMENTING COMPOSITION CHECK SHEET

In addition to handling different types of cement, HALLIBURTON offers a large number of additives which are used to modify and improve the basic cements for different well applications. These various materials are listed below and are classified under the general purposes for which they are recommended.

| APPLICATION | ADDITIVE | TYPES OF CEMENTS | BENEFITS | OTHER CONSIDERATIONS |
|---|--|---|--|---|
| REDUCE W.O.C. TIME (Accelerators) | HA-5 | Pozmix Cements and all API Cements | High Early Strength | Surface pipe, shallow wells and plugs |
| | Calcium chloride | | | Plugs for whipstocks - densified cements |
| | CFR-2 | API Class A, B, C and G Cements | Fast Setting | Lost Circulation |
| | Cal-Seal | | | |
| INCREASE THICKENING TIME (Retarders) | HR-4 | Pozmix Cements and all API Cements | Extend thickening time | Retarder for moderate temperatures |
| | HR-7 | | | Viscosity reducer-improves flow properties |
| | CFR-1 | | | Viscosity reducer-cement densifier |
| | HR-12 | Pozmix 140 and API Class D, E and G Cements | | Viscosity reducer-improves flow properties—retarder for extreme temperatures |
| | Diacel LWL | API Cement-Diacel Cement systems | | Low water loss |
| DECREASE SLURRY DENSITY | Halliburton Light Cement | Special high strength filler formulation | Low density - high strength - economical | Filler cement |
| | Bentonite | Pozmix Cements and all API Cements | Low density - economical | Filler cement additive - greater set volume |
| | Gilsonite | | Low density - high strength | Combats lost circulation |
| | Diacel D | | Low density - high yield | |
| | Perlite | | Low density | |
| INCREASE SLURRY DENSITY | Hi-Dense No. 3 | Pozmix Cements and all API Cements | Combat high pressure | Hard plugs for whipstocks Slurries up to 22 lb/gal |
| | Sand | | | Hard plugs for whipstocks Slurries up to 18 lb/gal |
| | Barite | All API Cements | | Slurries up to 19 lb/gal |
| | CFR-1 | Pozmix Cements and all API Cements | High slurry weight - less water—low slurry viscosity | Higher strength-faster setting by reduced water ratios Slurries up to 18 lb/gal |
| | CFR-2 | | | |
| LOST CIRCULATION | Gilsonite | All Cementing compositions | Combat lost circulation | Light weight slurry-high fillup above weak zones—bridges fractures - usable in squeeze cementing |
| | Tuf-Plug | | | Usable in drill mud for lost returns—blocking agent and fluid column lightener |
| | Perlites | Pozmix Cements and all API Cements (Usually mixed with 4% bentonite) | | |
| | Flocele | All Cementing compositions | Minimize lost circulation | Usable in drill mud for lost returns |
| | Cal-Seal Cement | API Cements | Fast setting for plugging lost circulation zones | Plug back, water shut-off and blow-outs |
| | Bentonite- Diesel Oil (gunk squeeze) | Use with or without Class A Cement (Not mixed with water) | Combat lost circulation, plug fractures, vugs and crevices | Used as spearhead in squeezing fractured zones |

Table 2 Continued

| APPLICATION | ADDITIVE | TYPES OF CEMENTS | BENEFITS | OTHER CONSIDERATIONS |
|------------------------------|-------------------------------------|--|---|---|
| LOW FLUID LOSS SLURRIES | Halad®-9 | Pozmix Cements and all API Cements | Reduces slurry dehydration | Reduces flow rate for turbulence in Bentonite cement slurries |
| | CFR-2 | | Reduces slurry dehydration - filtration control | Reduces flow rate for turbulence |
| | Diacel LWL | | Filtration control | Acts as retarder |
| | Halad®-14 | API Class Cements | Same as Halad-9 for temperature above 200°F. | Acts as retarder and dispersant |
| | LA-2 (Latex) | Pozmix Cements, API Class A, B, C, G and some Class E Cements | Fluid loss control on squeeze, liner and primary cementing | Good bonding and perforating qualities—resistant to acid and corrosive fluids |
| LOW FRICTION CEMENT SLURRIES | CFR-1 | Pozmix Cements and all API Cements | Provides turbulence at lower displacement rates - reduces hydraulic horsepower requirements | Retards thickening time - use above 200°F. |
| | CFR-2 | | | Dispersant used in densified cements |
| | Salt (NaCl) | | | Bonds to shales, bentonitic sands, and salt zones |
| | Halad®-9 | Bentonite cements (6% and higher) | | Provides low fluid loss properties |
| | HR-12 | API Class D, E and G Cements | | Retarder for extreme temperatures |
| | HR-7 | Bentonite Cements (all percentages) | | Retards thickening time |
| SPECIAL ADDITIVES | Salt (NaCl) | Pozmix Cements and all API Cements | Bonds to salt, shale and bentonitic formations - Improves flow properties | Accelerates in low concentrations—retards in high concentrations—more expansion than fresh water cements—increases slurry density |
| | Halliburton Red Plug Cement | Special high strength formulation | High strength, particularly when densified - low fluid loss - good flow properties - expansion upon setting - affords good placement time | Tolerates high percentage of mud contamination - low permeability - excellent bonding to clays and shales |
| | Silica Flour | Pozmix Cements and all API Cements | Reduces high temperature strength retrogression in cements | Reduces permeability of set cement - usable in oil, thermal recovery, steam injection and geothermal steam wells |
| | Mud-Kil® I | Pozmix Cements and API Class A, B, C and G and some E Cements | Combat effect of highly treated drilling muds on cement | Mud-Kil I neutralizes contamination effect of quebracho, starch, sodium carboxymethylcellulose, tannins etc. on cements |
| | Mud-Kil® II | Pozmix Cements and API Class A, B, C and G Cements | Combat effect of highly treated drilling muds on cements: Calcium lignosulfonate, chrome lignin, chrome lignite, etc. | Mud-Kil II neutralizes the effect of calcium lignosulfonate retarders used in some Class E Cements |
| | Radioactive Tracers-RAC-1 and RAC-3 | All cementing compositions | Helps locate top of cement or cement after squeeze | Helps locate leaks in casing with gamma log |
| | Casing-Kate™ | Applied to external surface of casing prior to running in hole | Improve bond at the pipe-cement interface | Increases shear bond and resistance to communication at pipe-cement interface |
| | DOC-3 | API Class A Cement | Thief zone treatment - squeeze - moderate penetration | Unlimited setting time - selective to water - mixed with diesel oil—does not activate until in contact with formation water |
| | DOC-10 | API Class A Cement | Thief zone treatment - squeeze - deeper penetration | |

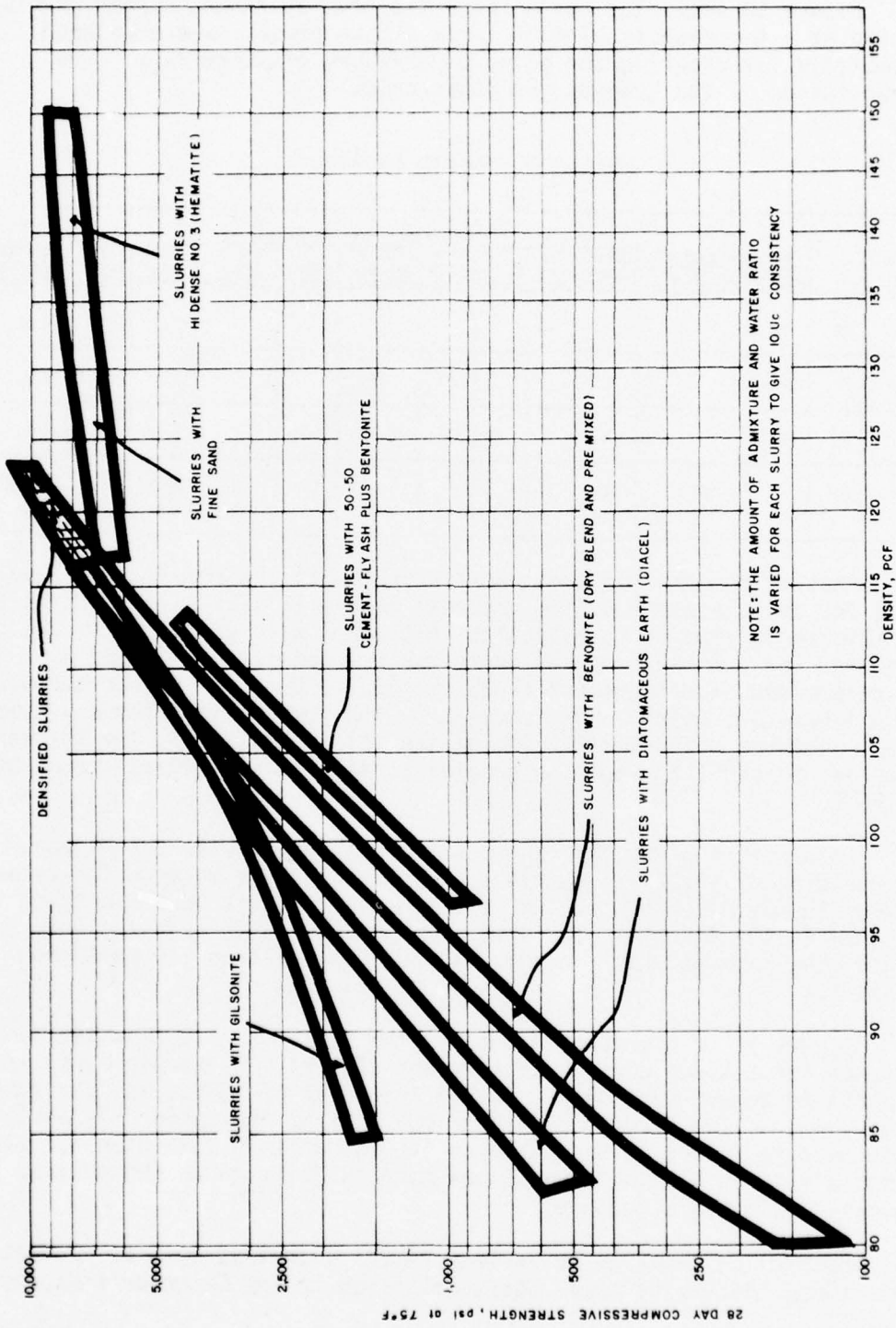


Figure 9. Compressive Strength of Seven Slurries at Varying Densities

Figure 10 shows the curing time for four different cement grouts tested at a temperature of 45°F. These four grouts were developed especially for grouting the piles of offshore platform legs. The compositions of the cements are given below:

TABLE 3
CEMENT SLURRY COMPOSITION FOR FIGURE 10

| Grout No. | U _c | Materials, Part by Weight | | | | | | | | | | | Density #/cu ft | |
|-----------|----------------|---------------------------|------|-------|---------------|---------|------|-----------|----------------|-------|--------------|-----------|-----------------|-------------|
| | | Portland Cement Type I | Cal. | Alum. | Gypsum Cement | Fly Ash | CaCl | Fine Sand | Sodium Citrate | CFR-2 | Hydrate Lime | Sea Water | | Fresh Water |
| 1 | 20 | 56 | | | | 44 | 1 | | | | | 41.2 | | 116. |
| 2 | 15 | 100 | | | 6 | | | 20 | 0.05 | | | | 46.7 | 122.7 |
| 3 | 15 | 100 | | | 6 | | | 200 | 0.05 | 0.50 | | | 43.7 | 142. |
| 4 | 10 | | 100 | | 6 | | | | | | 4 | 60.1 | | 113.4 |

Another concern for the cement slurries is the pumping time available for the placement of the material before it sets. The setting time, or thickening time as it is called in the oil well grouting, is the time required for a given composition to reach a consistency of 100 U_c. This is determined by methods set forth in API Standard RP 10B, or measured in a laboratory using a consistometer. The pumping time for any cement grout would be approximately 70% of the thickening time. The thickening time and pumpability would be greater at 40°F than at normal temperatures of 75°F.

In order to place the cement slurry through a pipe to the ocean floor, it would be desirable to maintain a dynamic balance between the cement slurry in the pipe and the sea water outside. It is possible to do this by knowing the friction head loss for the cement slurry used, then determining the rate at which to pump in order to maintain the balanced condition.

Figure 11 is a graph for determining friction head loss for dynamic balance for a known density of a cement slurry. An example is shown for a portland cement-sand slurry having a density of 130 pounds per cubic foot. A friction head of 510 feet/1000 feet is indicated. By applying this head to Figure 12 and assuming the use of a 3" I.D. pipe for placement, a rate of 120 cubic yards per hour is found to be the desired rate to maintain dynamic balance.

Helpful information on various cement slurries, such as w/c ratios, densities, thickening time, etc., are given in the Cementer's Handbook.¹⁶

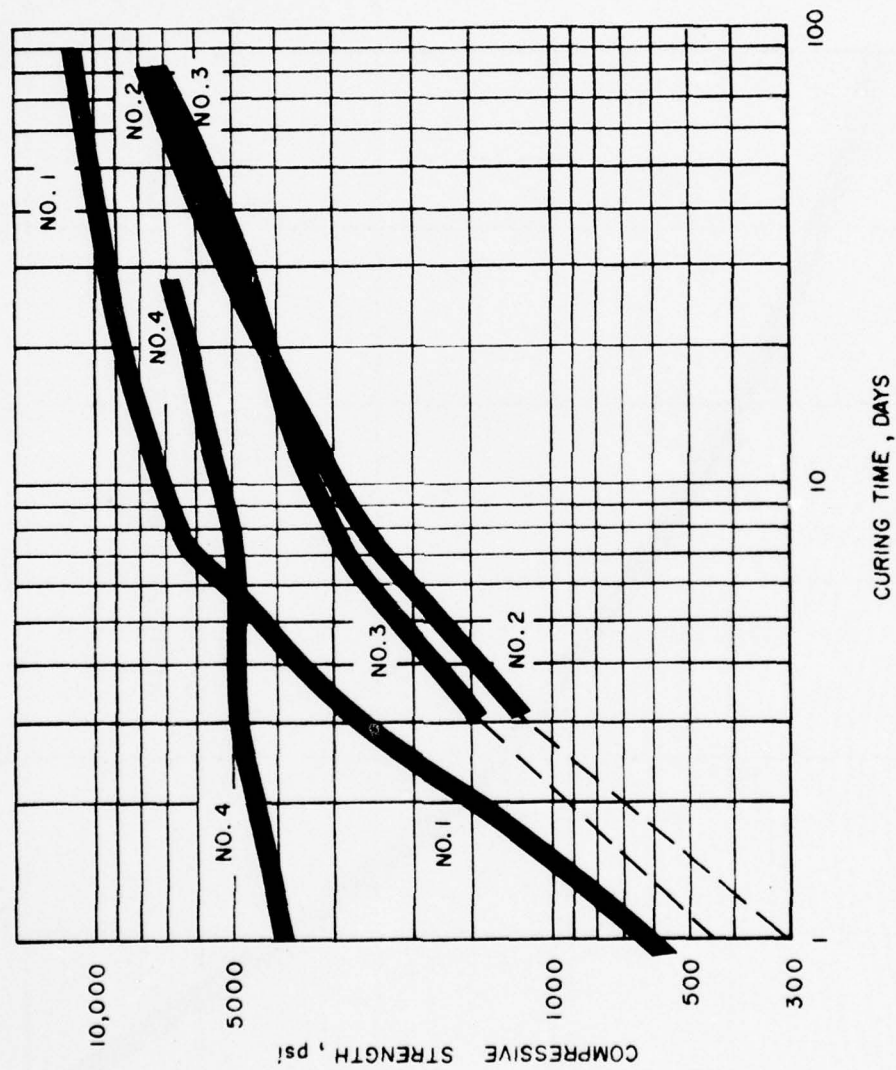


Figure 10. Curing Time for Four Cement Slurries at 45°F

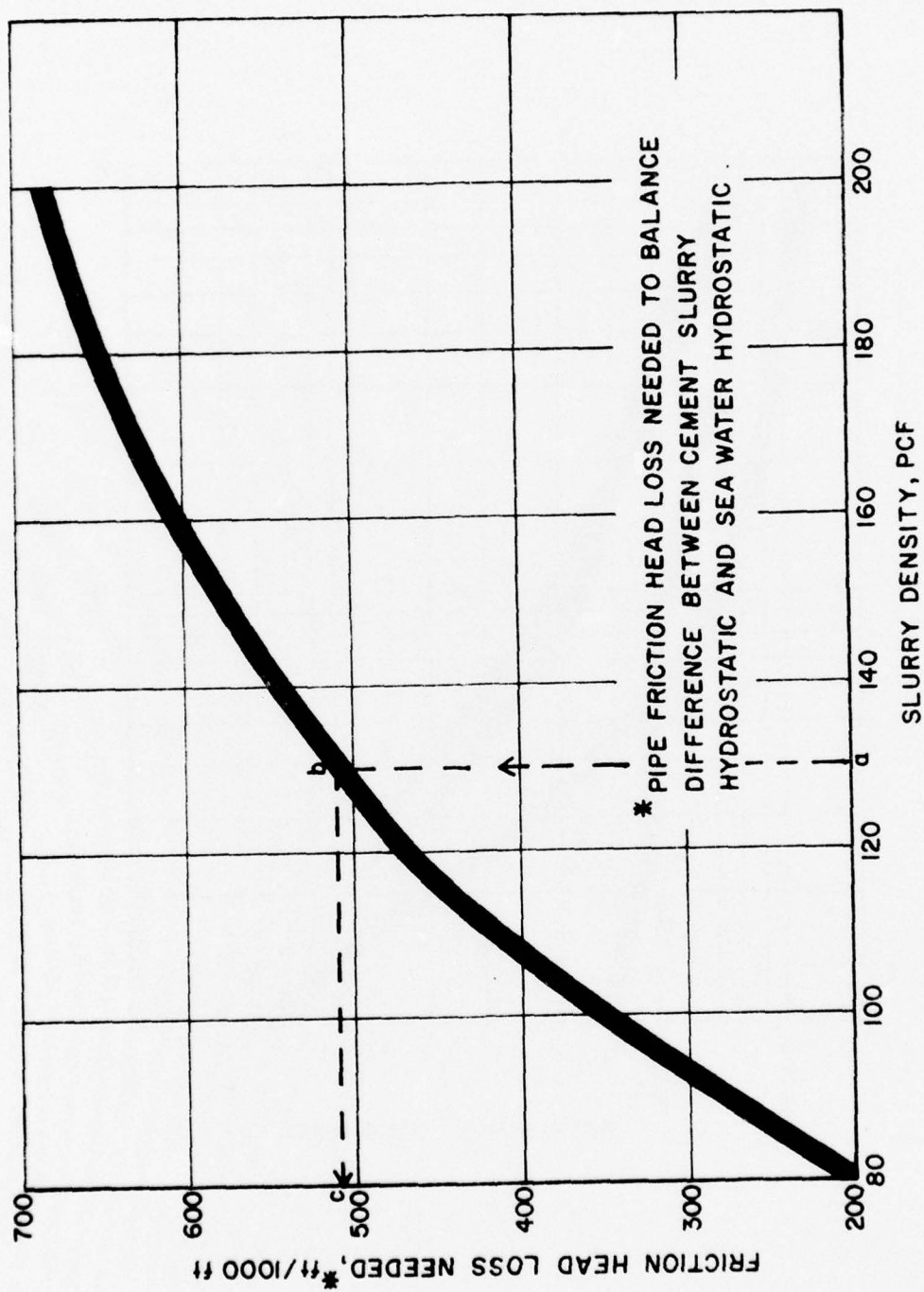


Figure 11. Graph to Determine Friction Head Loss of Cement Slurry

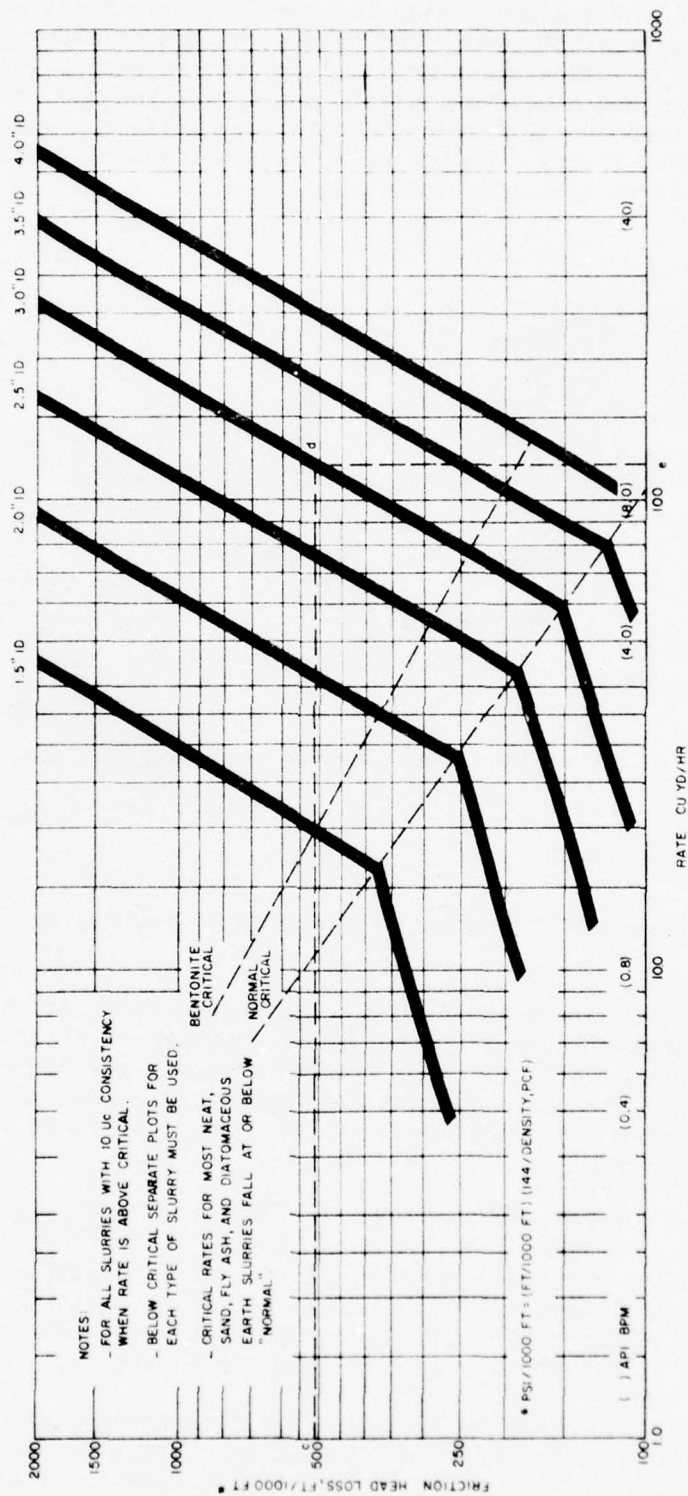


Figure 12. Graph to Determine Pumping Rate of Slurry for Dynamic Balance

(3) Equipment

The primary equipment used in cementing oil or gas wells is the positive displacement pumps used to mix the cement slurry and pump it into the well. Other equipment includes the accessory tools, such as mixers, cementing plugs to separate the cement and mud, and various down-hole tools used in specialized cementing operations. Figure 13 shows how the cement slurry is mixed continuously through a jet mixer and the resultant slurry is pumped into a well.

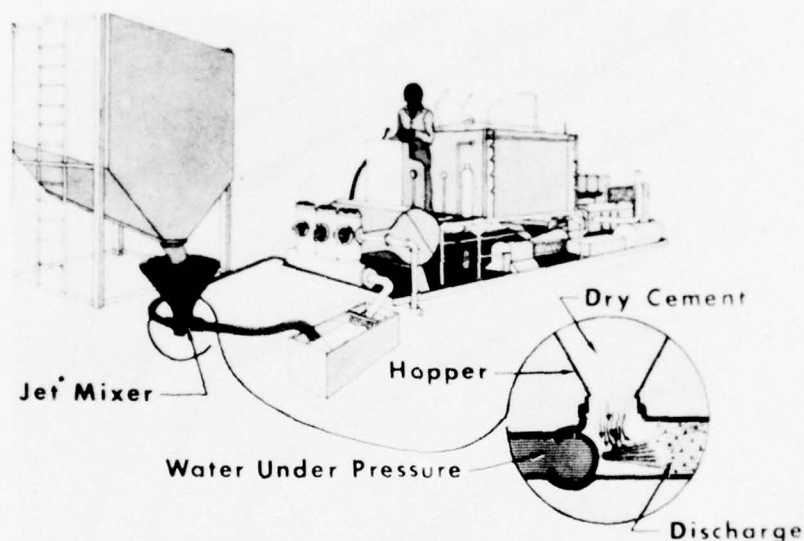


Figure 13. Schematic of Cement Slurry Mixing

The pumps are normally mounted on trucks or trailers coupled to diesel engines through a transmission, as shown in Figure 14. Duplex or triplex pumps with 4", 4-1/2" or 5" plungers are common. For offshore rigs, pumping equipment is normally mounted on steel skid bases and left on the platform until all wells are drilled. Figure 15 shows a skid unit of this type.

Cement can be stored and handled in sacks, but most jobs now use bulk cement. On land jobs, this is carried in trailers with pneumatic tanks, and the cement is moved by air to the mixing hopper. Figure 16 shows a unit of this type. For cementing wells in the ocean, either from a drilling platform or from a barge, skid-mounted pressure tanks are used. A unit of this type is shown in Figure 17.

Sand is not normally used in oilwell cementing, except occasionally sand passing U.S. No. 20 sieve is used as a weighting material, in quantities up to 1-1/2 parts sand to 1 part cement. The sand is dry sand which is blended with the cement before mixing.



Figure 14. Twin HT-400 Pumping Unit

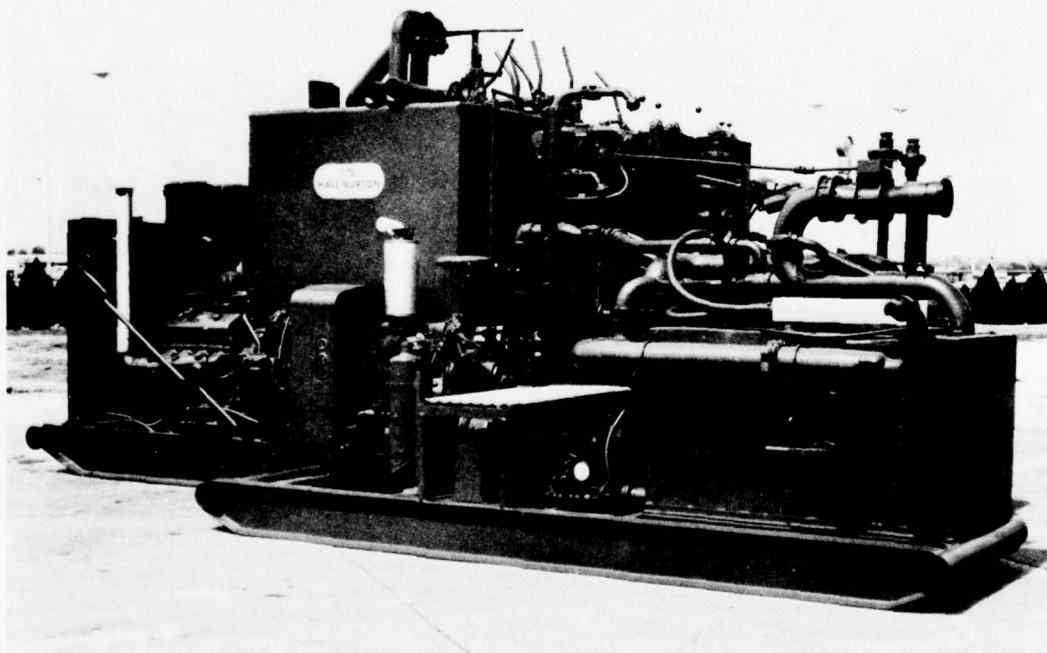


Figure 15. Diesel Powered Compact Skid Unit

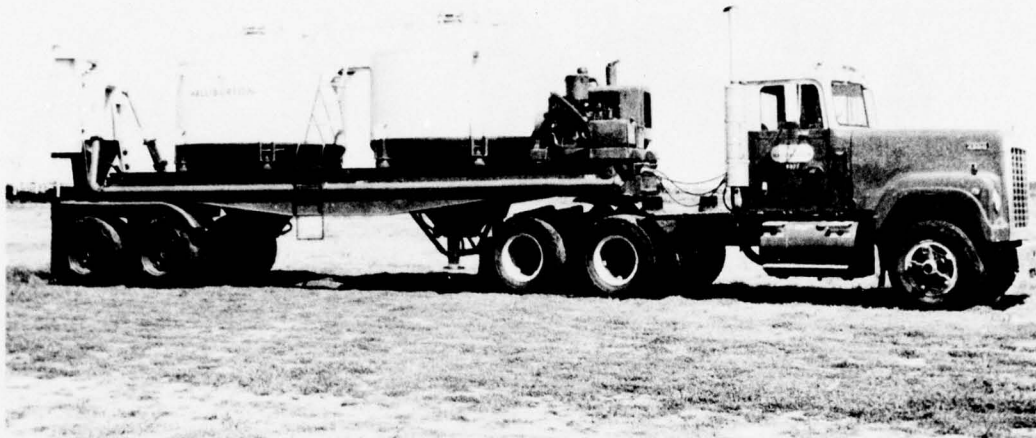


Figure 16. 660 cu ft Pneumatic Bulk Cement Unit

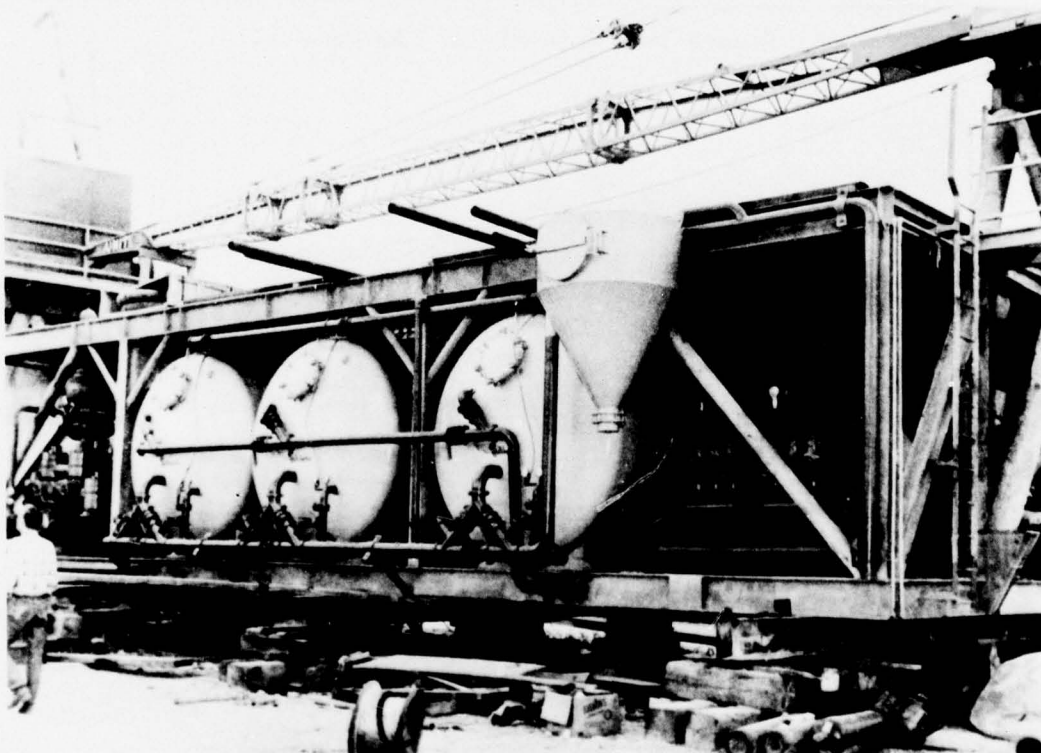


Figure 17. 3,750 cu ft Pneumatic Bulk Cement Unit
Being Installed on Off-Shore Platform

(4) Techniques

The oil field primary cementing operation is the original cementing which is performed immediately after the pipe or casing has been run in the hole. Figure 18 shows a diagram of a primary cementing job.¹⁷ This illustrates all of the tools and equipment used for this operation.

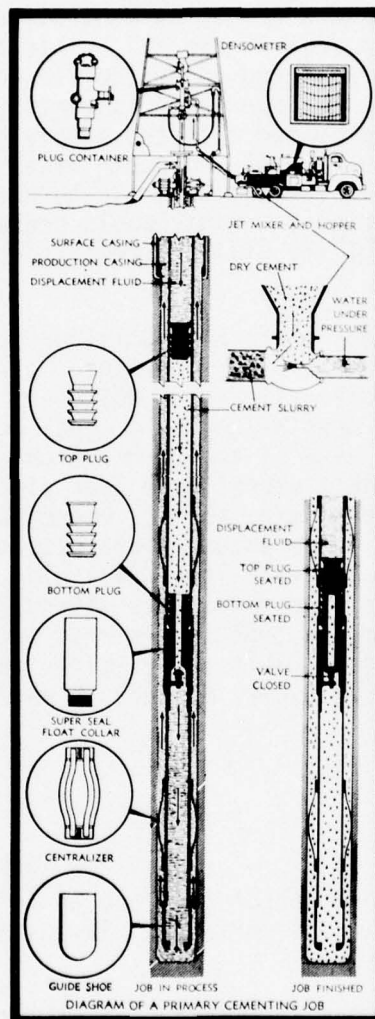


Figure 18. Diagram of Primary Cementing Job

The conductor, surface, intermediate and production strings of casing are usually cemented using the single-stage method. Single-stage cementing is accomplished by pumping a given amount of cement slurry through the

casing, with various types of top and bottom plugs, then out of the bottom of the casing, displacing the mud around the casing to form the protective sheath of cement. Different types of heads, such as single and double plug containers, are available for use in the continuous type of cementing.

In this type of cementing, the cement is introduced into a mixer hopper and mixed to a desired weight by controlling the amount of water flowing through the mixer (see Figure 13). This slurry goes into a receiving tub, where it is picked up by the placement pump and injected down the wellbore. Since the operation is continuous, any amount of cement can be injected, provided that the supply of cement and water is sufficient. For offshore mixing, the ocean water can be used, so the only contingent factor for large jobs would be the supply of cement materials. The single-stage technique would probably be the most practical for placement of the oilfield cements (or a modified version) on the ocean floor.

This method of placement has been utilized by the oil industry to place large volumes of cement slurry (cement, water and various additives) at depths in oil wells to 30,000 feet. Large volumes (4,136 cubic yards) have been placed at a depth of 5,010 feet in drilled holes at the Nevada test site of the former Atomic Energy Commission.¹⁸ Smaller volumes (2,200 cubic yards) have been placed at depths of 900 to 1,000 feet in large-diameter mine shafts, one of which was in south-eastern New Mexico. The large volumes were placed through pipe ranging in size from 2-inch through 6-5/8-inch drill pipe. The use of oil well slurries permitted longer placement times without the need of cleaning the tremie pipe from plugging that occurs when pumping concrete mixtures containing large aggregates. This is primarily due to the high percentage of cement in the pumped slurry mixture, high displacement rates and small particle sizes.

C. Problem Areas

As technology of placement of concrete in the ocean is advanced to depths where work has not been performed, job planning will be pushed beyond known capabilities.

All methods of concrete placement in open water will require sophisticated station-keeping equipment for cement placement equipment operating on the surface. Depending on depth of placement, station-keeping will have to be maintained within a few feet (10 feet) for shallow depths and up to 50 to 60 feet for deeper placement depths. Heave compensators will be necessary for controlling on-bottom placement of tools and equipment.

Sea state predicting capabilities will need to be utilized to the fullest extent. Most construction barges and associated equipment, such as work boats, cannot operate in over 5-foot sea states. In association with sea states, reliable weather information is needed to provide an adequate time span for completion of each succeeding construction phase. Since most placement depths for the study are below diver working depth, concrete placement should continue uninterrupted to completion because few tools are available for modifying surfaces or quality of placed concrete.

It is anticipated that logistics of material, manpower and equipment will require very careful planning in order for the job to proceed with maximum efficiency in meeting job requirements. The surface construction site will be quite congested due to the continuous supply of raw materials that must move to and across a very limited floating construction platform.

Once surface equipment for handling has been planned, mixing equipment must be sized to provide at least one complete backup system. Close control of raw materials and mix proportion must be maintained since there will be little or no chance for adjustment once the material enters the placement system. Information is well documented for pumping concrete through horizontal pipes and upwards,^{5,6} but very little information is available on the properties of concrete mixtures flowing downward through long pipes, either by gravity or by pumping. Information is available, however, for oil well cements.

Once the above problems have been solved, or the procedures have reached a desired level of competence, the on-bottom delivery method must be controlled. This may require a surveillance system and directional control of the on-bottom placement pipes or buckets. Large volume jobs will require movement of concrete placement points; therefore, on-bottom equipment must provide methods of guiding placement equipment to subsequent placement points.

Forms to produce a desired size and shape can probably be placed to depths of 2,000 to 3,000 feet. As the depth of underwater concrete jobs increases, containment methods and form placement techniques will probably involve more effort for construction than the movement of the concrete mixture to the placement point in the form or containment structure.

D. Limitations and Deficiencies of Current Technology

Current technology does not include a proven capability for placing concrete mixtures at depths of 1,000 to 20,000 feet in the ocean. Present experience of concrete placement underwater is very limited for depths greater than 200 feet. Several placement methods have been documented in operations to a depth of 200 feet.

The total concept of placing concrete mixtures on the ocean floor involves: (a) obtaining proper surface equipment, (b) transporting the concrete mixture from the surface to placement point on ocean floor, (c) controlling the rate and placement of the concrete mixture.

The surface equipment is common to all placement methods. It includes the mixing equipment, raw material storage and handling equipment. This type of equipment is available, but to date has only been used in sheltered waters at shallow depths on stable construction work barges. The station-keeping, material supply and mixing rate operations will require very tight scheduling for proper operations.

Transportation of concrete mixtures from the surface to the emplacement point on the ocean floor has not been accomplished for depths greater than diver working depths. The lack of information on concrete movement below these depths is probably due to the high cost of determining the in-place competency of the concrete structure. The methods of transportation are primarily surface methods, except for tremie pipe placement which is similar to well cementing methods; therefore, very little information is known about the flow and segregation of concrete mixtures downward through long vertical pipes with control of the discharge from the pipe.

Control of the concrete mix placement point and rate of placement has been limited to diver directed placement, which limits placement depths to the 400 to 500-foot range. Placement rate is also influenced by flow properties of the concrete mixture and the size of the placement line.

(1) Bucket Placement Method

Bucket placement has been accomplished to diver working depth, but can be placed at any depth provided a guiding system is available to direct the bucket to the emplacement point. Lifting and handling equipment restricts the volume (weight) of concrete that can be placed at one time. Since bucket placement is essentially a batch process, the time interval between each batch must be short enough to maintain the flow properties of the total cement mass. Even then, laitance can cause inferior quality. This method is generally limited to small quantities.

(2) Tremie Placement Method

Tremie placement of concrete mixtures has been used to depths of 200 feet with gravity differential used as the placing force. The end of the tremie pipe submerged in previously placed concrete must be closely controlled to permit free flow of concrete out of the pipe without flowing at a rate high enough to disturb the surface of the in-place concrete. Flow rate out of the tremie pipe is difficult to maintain at a rate that will prevent bridging of the material in the pipe. This is especially true when using a batch method to feed the tremie pipe.

Bridging requires movement of the pipe to dislodge the bridge or plug. Unless continuous flow with a positive hopper level is maintained, air can be trapped in the concrete column and compressed, which can result in flowing concrete out of the top of the tremie pipe or into the placed concrete. The surface area covered by concrete, placed by tremie pipe using conventional mixture, is approximately 350 square feet or 15 feet from the tremie pipe. This would require multiple pipes for large surface pours, or entail moving the injection pipe many times.

(3) Pumped Concrete Method

Concrete placement using pumps would probably increase the cost of concrete placement for shallow, calm waters, but should not increase costs for large volume jobs in deep water. Pumped concrete mixtures require more precise mix control, as well as raw material quality control, but this added effort can result in less plugging or bridging. Estimating friction pressure loss from concrete rheology properties is not a well-developed technology, and segregation through long vertical pipes has not been fully evaluated.

(4) Pumped Cement Slurry Method

Pumped cement slurries could be placed at nearly any depth on the ocean floor using present materials, methods and equipment. The pumped slurry would need to be controlled at the point of exit from the placement pipe, since normal oil field placement is done in a drilled hole and utilizes the hole for containment of the slurry. If a containment form is placed on the ocean floor, cement slurries could be used only if the form is tight, since the slurry will readily flow horizontally in the form. For final compressive strength above 2,500 psi, a cement slurry usually has a heat of hydration too high for large mass applications.

(5) Preplaced Aggregate Method

The use of grout intruded aggregate is limited by the depth the aggregate can be placed with the grout pipes embedded in the aggregate. The low pump rate required limits the size of each placement, depending on the flow properties of the grout. Depth limit under present technology would be diver working depth, or 300 to 500 feet.

(6) Bagged Concrete Method

There is no limit to the depths where bagged concrete can be used, provided that the bags must be placed in the desired place by some means.

3. NEW CONCEPTS FOR OCEAN CONCRETE PLACEMENT

Concrete mixtures have not been placed in water depths of 1,000 feet to 20,000 feet. The placement of concrete mixtures at these depths has only been accomplished in the oil industry in drilled holes using grout mixtures containing aggregates which pass a U.S. No. 4 sieve. The concepts set forth in the following discussions utilize construction methods with some adaptations of oil well cementing practices.

Material placement methods are primarily governed by the physical and rheological properties, and the pumping and setting times of the concrete mixtures. Most placement techniques will be developed for a given job requirement, site conditions and in-place strength development of the concrete mixture. One of the governing conditions for any placement technique is the concrete mixture. Flow properties of the concrete mixtures are of prime importance and must be closely controlled, since placement is primarily a material transportation problem. It would be of benefit to the material supply, mixing and placement techniques to keep particle size and shape used in the mixture as uniform as the required concrete strength requirement will permit. The uniform size and shape throughout the job permits more control of all phases of the construction process. This uniformity of materials gives less problems when storing, transporting, mixing and pumping the final concrete mixture.

A. Placement by Tremie Method (Open System)

(1) Functional Description

This concept is a variation of the tremie pipe method, in which inner pipe is used to supply concrete to the balance point of concrete to sea water as shown on Figure 19. The annulus between the inner and outer pipe is open to the atmosphere, thus allowing the concrete level to vary as needed. It also acts as a vent for any air trapped in the inner pipe.

The outer tremie pipe is run to desired depth and allowed to fill with water. A wiping plug is then inserted into the pipe and the concrete mixture introduced on top of the plug. The plug and concrete mixture travels down the pipe, expelling the water out of the tremie pipe. After the calculated volume of concrete needed to give a concrete height to the balance point has been placed, the inner pipe is run to the balance point. Concrete mixture can then be supplied to the balance point through the inner pipe to eject the plug from the end of the pipe and start placement of the concrete mixture on the ocean floor.

The smaller inner pipe provides a higher resistance to flow, offsetting the hydrostatic differences between the concrete mixture and sea water. Based on 8.5 lbs/gal sea water and 22 lbs/gal (165 lbs/CF) concrete, their respective hydrostatic pressures are 0.44 psi/ft and 1.14 psi/ft; therefore, one foot of sea water is balanced by 0.39 foot

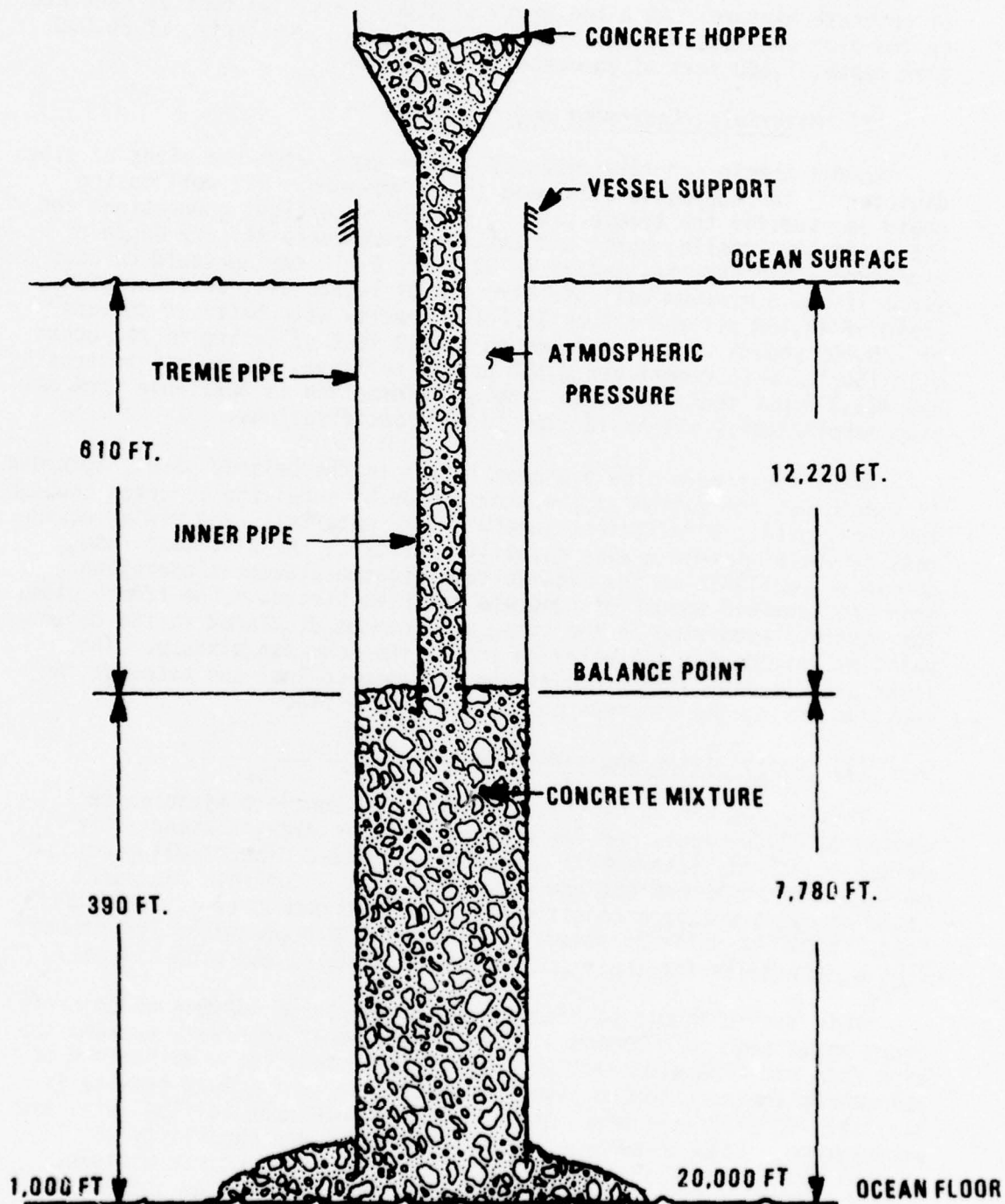


Figure 19. Tremie Pipe Placement - Open System

of concrete mixture. At a sea depth of 1,000 feet, 390 feet of concrete in the pipe are required for hydrostatic balance; similarly, at 20,000 feet depth, 7,800 feet of concrete are required.

(2) Materials, Equipment and Technique

Normal tremie concrete mixtures can be used, with the sizes of pipes dictated by the aggregate size used in the mixture. Oil well casing could be used for the tremie pipe to provide watertight connections and the necessary tensile, burst and collapse resistance for any depth of placement. For example, 5-1/2" — 23 lb/ft P-110 casing could be used since it has a minimum collapse strength of 14,520 psi, an internal yield of 13,580 psi and a tensile load capacity with buttress threads of 725,000 pounds. Maximum loads on 20,000 feet of casing in the ocean with 150 lb/cu ft cement are 8,656 psi in collapse, 13,160 psi internally and 401,350 psi tensile. This type of information is available from all pipe manufacturers who build pipe to API specifications.

After the tremie pipe has been filled to the balance point, concrete is forced out the bottom of the tremie pipe by supplying concrete through the inner pipe. A sufficient supply of raw materials, and mixing equipment having a minimum mixing capability of twice the placement rate, should be available on the site to complete the placement operation. When the required amount of concrete has been placed in the tremie pipe, the concrete remaining in the inner pipe can be displaced to the balance point by introducing sea water on top of the concrete mixture. The inner pipe is then lifted out of the concrete so that the seawater can continue moving the concrete out of the tremie pipe.

(3) Capabilities and Limitations

This system can be used for placement of concrete mixtures in depths to 20,000 feet, and for volumes up to several thousand cubic yards. Depth of placement is governed by surface pipe handling equipment, mixing equipment and raw material supply. Concrete placement could be performed from construction barges to depths of around 5,000 feet. Floating drilling vessels would probably be required for greater depths, primarily for their speed in pipe handling and pipe storage.

This method should be capable of placing large volumes of concrete. Lines would require cleaning with a wiper plug at intervals to keep the pipe open and free flowing. A close control needs to be maintained on volumes of concrete in the pipe (height), since only fluid gravity is available to clear the pipe when plugged or when reduced flow rates are encountered. Open ocean sea states would limit the capability to control the depth of the tremie pipe in the placed concrete mixture. The use of heave or motion compensators on the tremie pipe suspension system would be necessary for rough seas.

(4) Evaluation

This system can be used to place small volumes to depths of 20,000 feet at a single point. Movement of the pipe to a new placement point would probably require removal of the inner pipe to start a new pour. If bridging or plugging of the pipe occurred during placement, restarting the movement of the concrete mixture would require pipe movement or pumping to force the mixture from the pipe. Obviously the system requires handling two different pipes with the associated problems of supporting and maintaining control of pipe depths.

B. Bucket Placement Through Tremie Pipe

(1) Function and Equipment Requirements

A similar concept to the prior one would be the use of a bucket in place of the inner pipe to transport the concrete mixture to the balance point, as shown on Figure 20. The diameter of a tubular bucket would be sized to operate inside the tremie pipe. For example, if a 12-inch diameter tremie pipe was selected, a bucket made from 10-inch pipe could be used. To carry 1 to 3 cubic yards of concrete, bucket lengths of 50 to 150 feet would be required. The lowering rate would be up to 500 ft/min, with retrieval at rates up to 1,000 ft/min. This would give an average travel time of 3 min/1,000 ft plus loading and dumping time. It is estimated that a two-cubic-yard batch would take 15 minutes to load and 10 minutes to dump, thus giving a cycle time of 28 minutes for dumping at 1,000 feet.

The use of an open-top bucket in place of the inner pipe would reduce the pipe handling requirement of the construction barge or drillship, but would probably reduce the placement rate by some 40% from the rates attainable with the inner pipe method. Mixing equipment requirements and material storage would be the same as for the inner pipe method. The material placement vessel would require the addition of a winch having line and hoist capability to handle the bucket, line and concrete weight.

Placement of concrete at the balance point by bucket would reduce the possibility of entrapping air in the column of concrete. The longer time required to deliver the concrete by bucket would allow better control of mixing processes, assuring proper concrete mixture before being placed in the system. When the desired volume of concrete has been placed in the pipe for delivery, the bucket could be used to place sea water in the tremie pipe to force the concrete out of the pipe.

(2) Capabilities and Limitations

The lower rate capacity of the system would limit the size of concrete placement to several hundred cubic yards through one tremie pipe.

If several tremie pipes are utilized, large volumes can be placed with one bucket hoist system supplying concrete while pipe handling

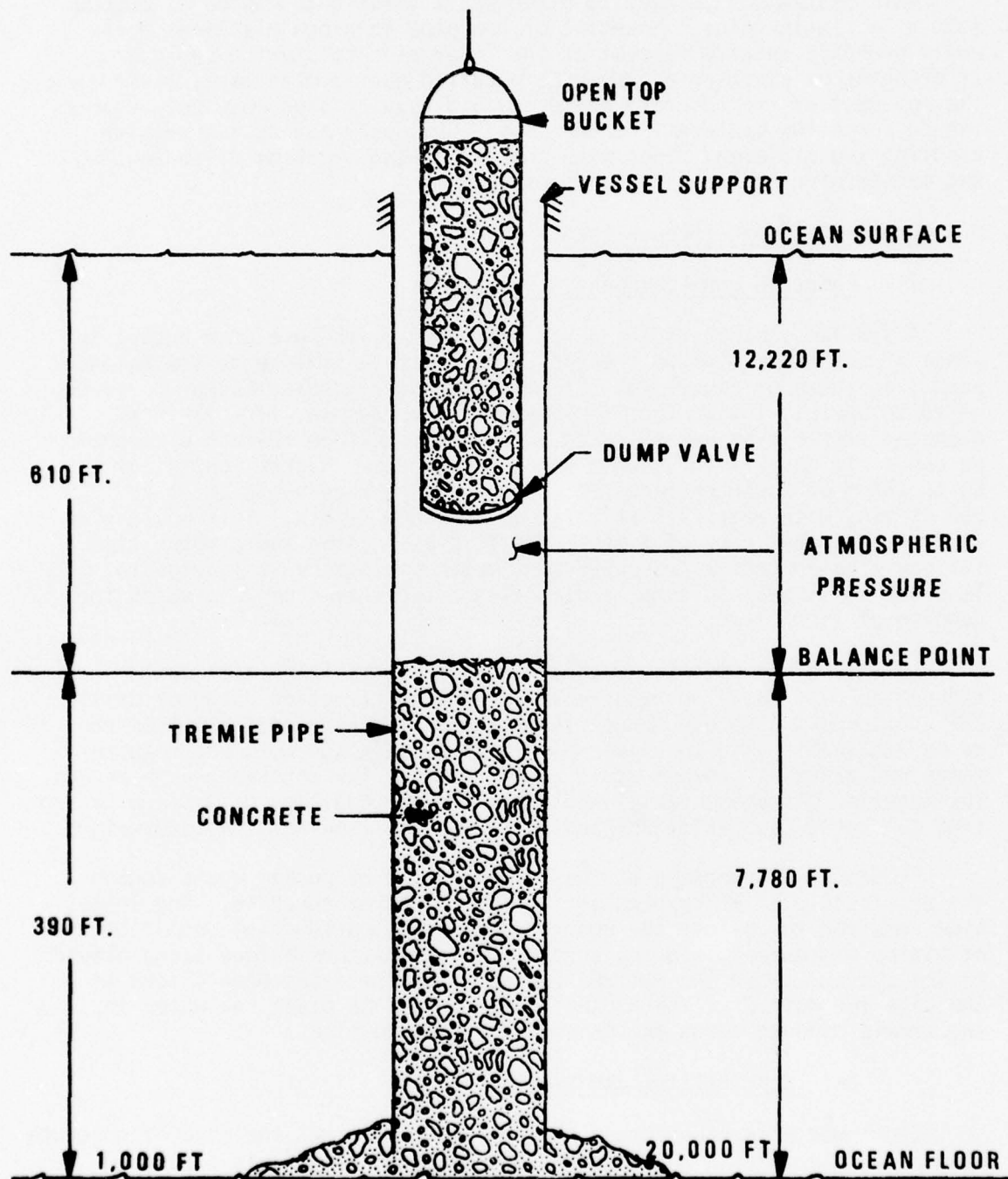


Figure 20. Bucket Placement in Tremie Pipe

equipment moves tremie pipes to subsequent placement points. The volumes of concrete placed would require close control of setting time with regard to placement rates to allow adequate cycle time of the bucket. The bucket dump method could be used to determine the height of the concrete mixture in the tremie pipe on each dump, and thereby control the rate of release of concrete from the tremie pipe without pipe movement.

(3) Evaluation

This method would lend itself to rapid mobilization jobs, especially where small volumes (several hundred cubic yards) are to be placed at depths of 1,000 to 5,000 feet. As depth of placement increases, the speed of mobilization and volume placed would be reduced. Placement of concrete mixtures could be accomplished with less skilled crews than other methods.

C. Placement Through an Inclined Tremie Pipe

(1) Functional Description

This concept of concrete mixture placement utilizes an inclined tremie pipe suspended from a pipe lay barge and flotation chambers, for placing large and small volumes of concrete to depths of 1,000 feet. The slope of the inclined pipe is 1:2 or greater to provide a closed chute to feed a short vertical section at the placement site, as shown in Figure 21. The mixture could be a tremie pipe mixture with slightly higher slump to provide mobility through the pipe.

(2) Materials, Equipment and Technique

The use of a pipe lay barge would provide a stable platform with pipe storage and handling facilities. The work deck could accommodate the mixing system for high placement rates. The anchorage and barge movements could be utilized for movement of the tremie pipe to new locations or to make a continuous pour in a long trench or form. Control of placement rates can be accomplished by balancing the concrete vertical height against the water depth, as in the vertical tremie pipe placement. The same methods for cleaning the vertical tremie pipe can be used on the inclined pipe. The technology for pipe handling is available, so this concept would only require developing the mixing, material storage and flotation devices.

(3) Capabilities, Limitations and Evaluation

The surface equipment is available for this type of concrete placement with very minor modifications. Surface equipment is available to stay on work station in up to 10-foot seas. High placement rates could be attained up to mixing and material handling equipment capabilities by selecting proper tremie pipe size. Placement depths would be limited with present equipment to depths of 1,000 feet. As experience is

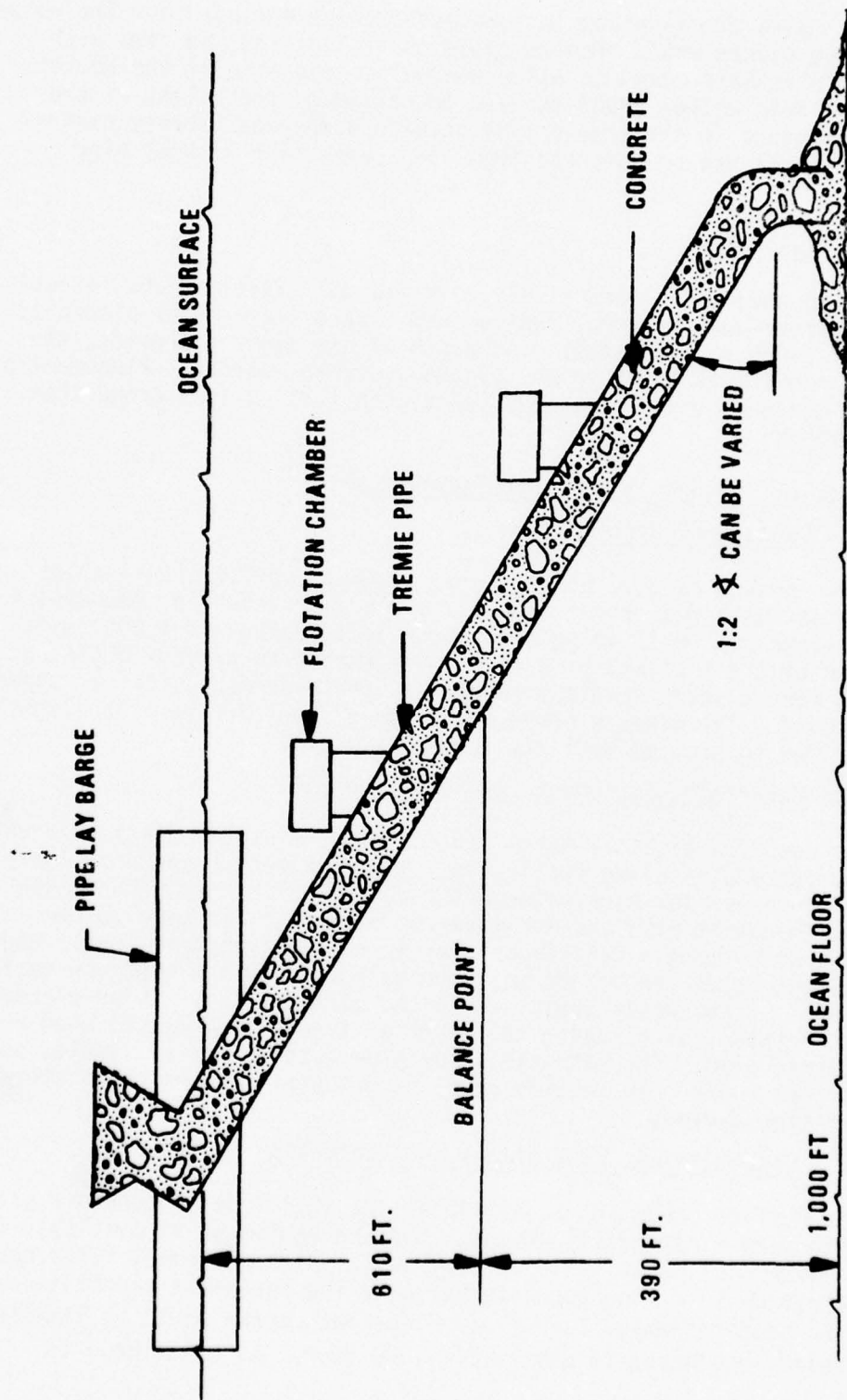


Figure 21. Placement by Inclined Tremie Pipe

accumulated, depths could be increased to 2,000 or 2,500 feet. This method could be used for placing large volumes of concrete at shallow depths where placement points must be moved continuously, or placement over a large area is required.

D. Bucket Placement

(1) Functional Description

Concrete mixtures could be placed by buckets, using a cable to guide the bucket to placement point, as shown in Figure 22. The guide cable could be anchored to the ocean floor with an explosive anchor, and the cable used to guide a tubular bucket to the placement point. This method could be used to place small volumes at depths up to the hoist and line capabilities available.

(2) Materials, Equipment and Technique

This type of placement could be performed off construction barges or any type of vessel capable of maintaining position over the placement point. The necessary size winch and hoist could be easily obtained to work in conjunction with a mixing and material handling system. The bucket would need to be designed for automatic opening of the dump valve when emplacement point is reached. One method could be a trip-type sleeve on the guide cable to pull the valve open when the bucket reaches the dumping depth. Another method could be a knife shear seal on bottom that would shear when impacted on ocean bottom or on a receiver pipe. Volume of the bucket could be adjusted to demands by increasing length after basic diameter has been determined, based on concrete mixture aggregate size. A 24-inch diameter bucket 45 feet long would be feasible. This size bucket would hold 5 cubic yards of concrete.

(3) Capabilities and Limitations

The bucket placement method would be capable of placing small volumes (5 to 8 cubic yards) of concrete at any depth compatible with anchor, cable and hoist capabilities. The cycle time for the buckets would affect the total volume of concrete that could be placed in a given time. The cycle time would be the time for a round trip to bottom with the bucket plus loading and dumping time. Rates of 300 to 700 ft/min do not appear to be unreasonable. Retardation of concrete setting time could increase the volume placed at deeper depths. Bucket length would be affected by currents and sea states, since the guide cable is a flexible member. These effects can be offset with heave compensators and with stiffer tubular members for bucket construction. The method would result in more laitance due to the batch placement.

(4) Evaluation

The bucket placement system could be mobilized from existing equipment for small volume jobs at shallow depths. As depth and volumes

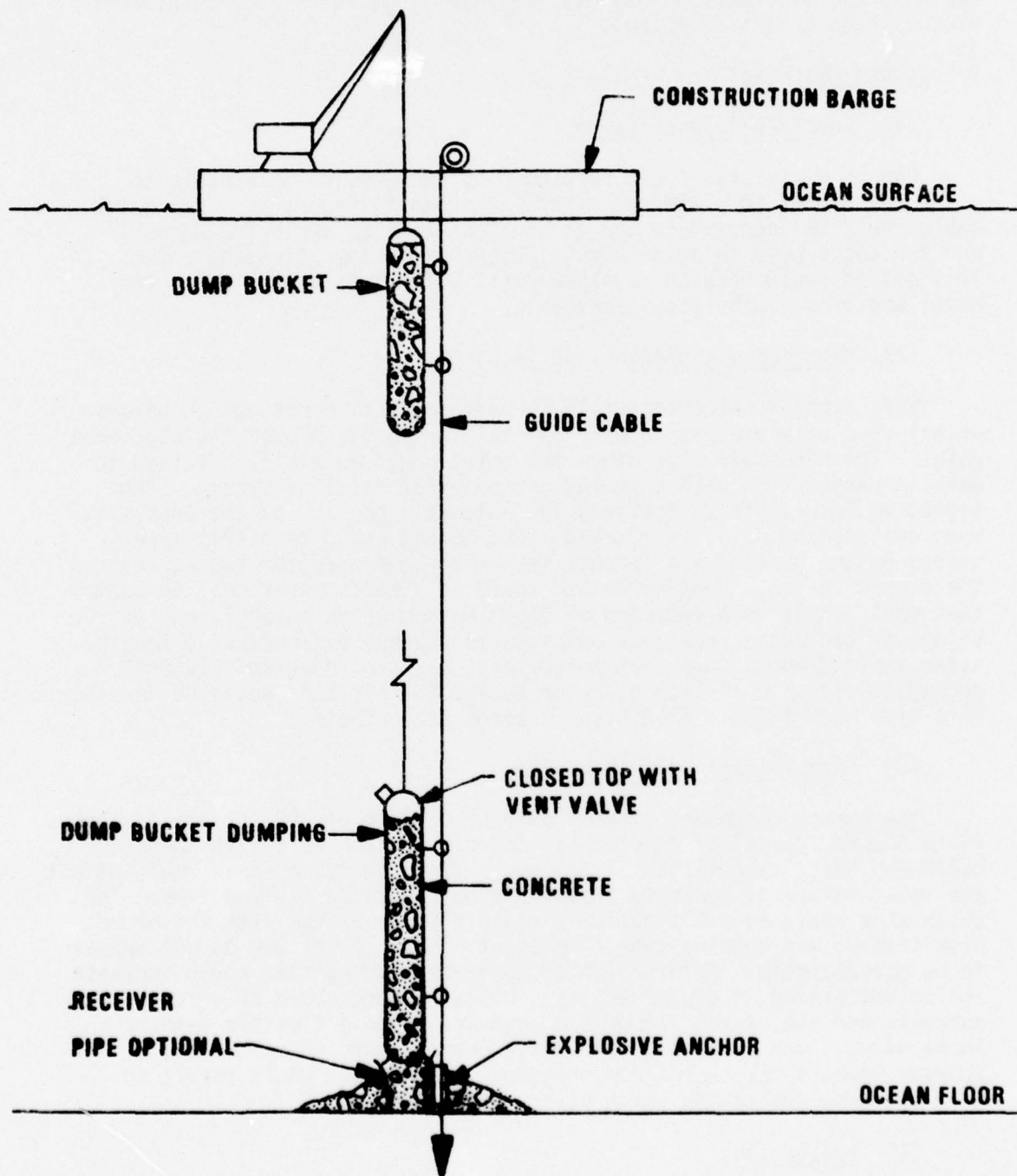


Figure 22. Bucket Placement - Cable Guided

increase, refinement of equipment would need to be accomplished for proper placement of material. The method would produce more laitance due to the stop-start movement of the placed concrete. It would also result in more wastage of placed material than continuously placed concrete, since the top of each batch would be in contact with the water, which would tend to degrade the concrete and possibly require more material.

E. Placement by Pumped Tremie Method (Closed System)

(1) Functional Description

This pumped tremie method of concrete placement would use a vertical tremie pipe that is run to emplacement depth with a wiping plug placed in the top of the tremie pipe. The concrete mixture would then be pumped into the tremie pipe on top of the wiping plug and the plug displaced by the concrete. When the plug reaches bottom, it is expelled from the tremie pipe by the concrete mixture, as shown on Figure 23.

The concrete pump acts as a variable flow-control device in a closed system, which permits only the amount of concrete mixture to be delivered out of the tremie that is introduced into the tremie pipe by the pump. The flow of concrete into the tremie pipe is controlled by the pump output, but once the material is in the pipe its falling rate will be governed by the frictional resistance of the material moving through the pipe. When the hydrostatic pressure of the concrete becomes greater than the hydrostatic pressure of the water, the concrete will move through the pipe faster than it is introduced at the top by the pump, thereby separating the column of concrete. This void moves with the concrete column until the concrete above can close the void. Since the system is closed, and the void does not contain atmospheric air, the concrete above will eventually fill the void. This action takes place above the balance point; therefore, discharge from the tremie pipe is controlled by the amount of concrete pumped into the pipe. The pump also provides an operational safety factor by being able to apply a pressure above gravity head. This added pressure assists displacement of wiping plugs and movement of concrete mixture to clear the pipe when partial plugging or bridging occurs.

(2) Materials, Equipment and Technique

Pumped tremie concrete requires close control of mixtures to aid in pumping operations. The slump of a concrete mixture is the method presently used to judge the pumpability of concrete, but this is not a good indicator of the rheological properties. The rheological properties control the friction pressure that resists the flow of the concrete mixtures. The resistance to flow can be utilized to offset the difference in hydrostatic pressure between sea water and concrete mixture. Sea water exerts a pressure of 0.44 psi/foot and concrete 1.14 psi/foot, giving 0.70 psi/foot in friction pressure that is needed for balance. After selecting the pipe size for a given job and considering equipment

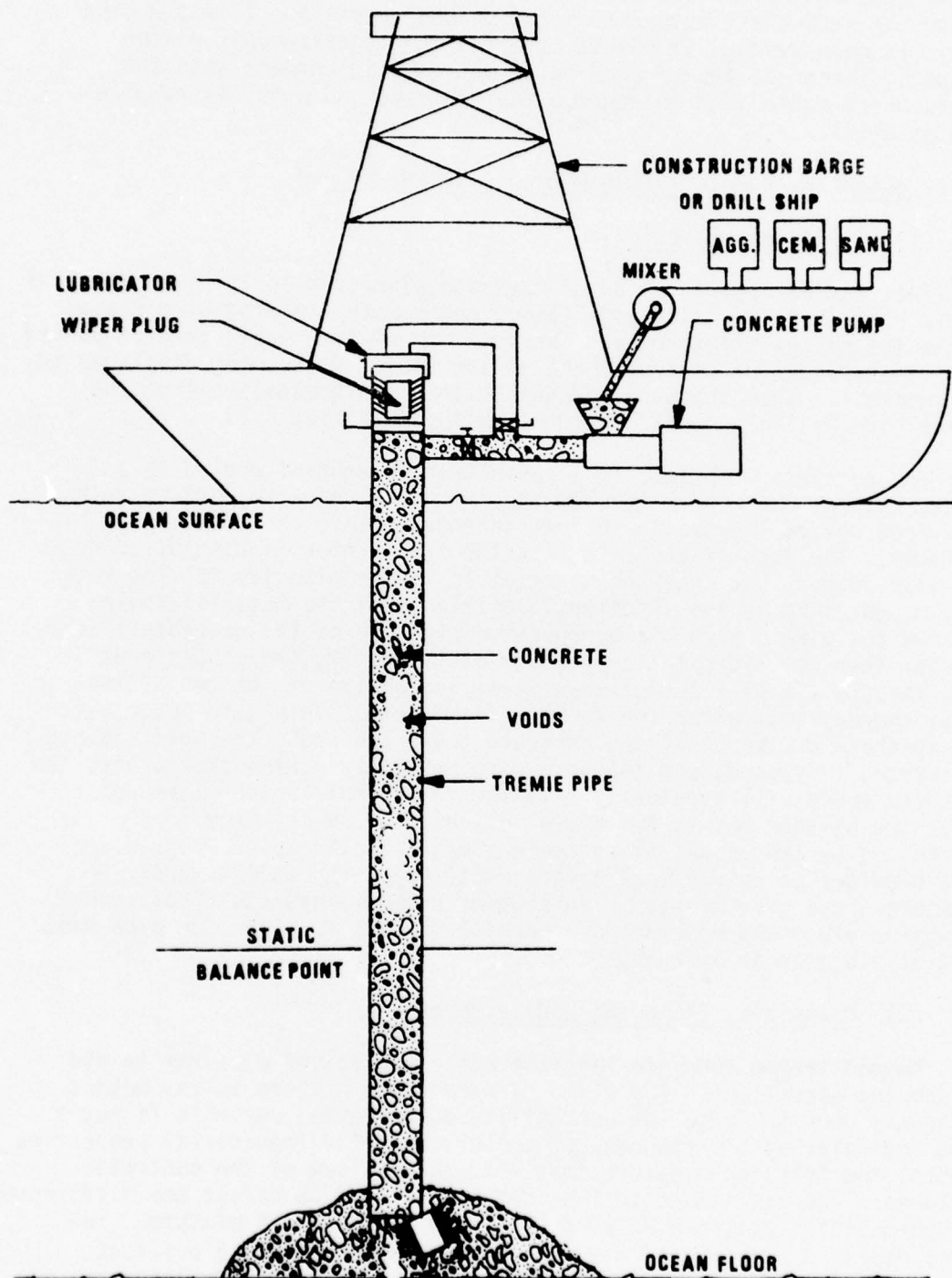


Figure 23. Pumped Tremie Placement - Closed System

capabilities, the slump or rheological properties of the concrete can be tailored to produce the required friction pressure. Table 4 shows the friction pressure for 3 line sizes at 5 different slumps and 4 different flow rates.¹⁰ A friction of 70 psi/100 feet can be obtained with concrete having a slump in the 3- to 5-inch range for 3-inch pipe at rates of 40 cu yd/hr or more. As the pipe size increases, slump must decrease and/or rate must increase. Typical concrete pumps can place from 5 to 125 cubic yards per hour; therefore, one pump would be adequate for most jobs, but standby or backup equipment would be needed to assure continuous operation. The tremie pipe needs to be wiped by displacement of a wiper plug every few hours to assure an open pipe for continued placement. The wiping plug can be introduced into the system through a chamber or lubricator to prevent the introduction of air into the system.

Table 4
Line Pressure Data for Pumped Concrete

| Slump Inches | Line Pressure psi/100 ft for Rate Shown | | | |
|-----------------|---|--------|--------|---------|
| | 20 yph | 40 yph | 60 yph | 100 yph |
| <u>3" Line</u> | | | | |
| 2 | 120 | 240 | 350 | - |
| 3 | 80 | 170 | 230 | 400 |
| 4 | 60 | 120 | 180 | 280 |
| 5 | 40 | 90 | 130 | 220 |
| 6 | 30 | 60 | 80 | 140 |
| <u>4" Line</u> | | | | |
| 2 | 88 | 150 | 240 | 340 |
| 3 | 62 | 105 | 170 | 230 |
| 4 | 44 | 75 | 125 | 170 |
| 5 | 31 | 55 | 85 | 125 |
| 6 | 20 | 37 | 60 | 80 |
| <u>5" Line</u> | | | | |
| 2 | 45 | 105 | 150 | 230 |
| 3 | 36 | 70 | 100 | 185 |
| 4 | 26 | 50 | 75 | 130 |
| 5 | 20 | 35 | 55 | 90 |
| 6 | 12 | 24 | 30 | 65 |

-From Challenge-Cook Brothers

(3) Capabilities and Limitations

This system can be used on small or large volumes at depths from 1,000 feet to 20,000 feet. Care should be taken to prevent atmospheric air from entering the discharge pipe. Air pockets in the column of cement will increase the pressure necessary for the pump to inject the concrete, as well as create an undesirable situation in the concrete placement. Pipe size should be carefully selected to provide only as large a pipe as absolutely necessary, since the flowing friction of the concrete mixture through the tremie would offset the hydrostatic pressure differential between the concrete mixture and sea water. Any reduction in concrete mixture weight would reduce the friction pressure differential and give more positive control of placement techniques.

Surface equipment for placement depths of 1,000 feet to 2,000 feet could operate from a barge with hoist and mixing equipment on the deck. Concrete materials could be supplied from other barges if necessary. During placement at greater depths, more sophisticated pipe handling equipment would be needed, perhaps up to the capability of modern, dynamically-positioned drill ships. This capability would be needed for handling long lengths of pipe efficiently and speedily.

(4) Evaluation

The pumped tremie method of concrete placement offers more capability for placing large volumes of concrete at higher rates than other methods. More control of placement rates and concrete movement is available from the closed system. Equipment costs would probably be higher than other methods; therefore, the most economical use would be where large volumes need to be placed in a short period of time.

Raw materials and the mixing process would need to be closely controlled to provide the most uniform mixture possible. Mixtures could be developed to provide a resistance to flow that is compatible with the size tremie pipe used and the depth of placement.

4. RECOMMENDATIONS FOR RESEARCH AND DEVELOPMENT EFFORTS

There are several areas where research is needed before concrete can be placed at depths below 500-600 feet or placed in larger quantities. In some instances, existing technology for cement slurries can be broadened to encompass concrete materials. Existing technology for pumping concrete on land has a high potential for adaptation to placing concrete underwater with minor research efforts. Some research efforts may be required for completely new approaches.

Eight recommendations are presented for consideration. These deal with research on the concrete material properties, equipment design and techniques of placement. These are presented in the suggested order of priority for research and development efforts.

A. Determining Rheological Properties of Concrete Mixtures

Placement of concrete in the ocean requires very close control of all job operations as placement depths and volumes increase from the present state-of-the-art. The first area of control is the concrete mixture. Since placement through tremie pipe offers higher placement rates at greater depths, the resistance to flow of concrete mixtures through vertical pipes needs to be determined. The resistance to flow can be utilized to offset the hydrostatic pressure differential between the concrete and sea water for a given placement rate and pipe size. Since the mixture must be transported longer distances, the rheological properties of the concrete mixture are very important and need to be more precisely defined.

Methods now used by oil field service companies to determine the rheological properties of oil well cements could probably be extended for use on concrete mixtures. The measuring system would be similar, but with the inclusion of vertical pipe to measure properties on material moving downward. Larger pipes and concrete pumps would be needed to adequately handle the concrete mixtures. As the data is obtained on the flow of concrete mixtures in pipe, it needs to be correlated to some property of the mixture that can be measured on site.

B. Field Test Method for Control of Pumped Concrete Mixtures

The pumpability of a concrete mixture is presently determined by slump and past experience. It has been found that slump of the mixture does not adequately describe its pumpability. Information is available on mixtures for pumping horizontally and upward through a vertical pipe. Very limited information is available on concrete for pumping downward through a vertical pipe.

Therefore, a field instrument should be developed to measure the rheological property prior to introducing the concrete into the placement handling system. The instrument may be a large viscometer similar

to a rotating type viscometer, but with the capability of handling large aggregates. This would be a major research project due to material, manpower and time required for tests, but the risk of failure would be small. This project is given high priority because its completion is a prerequisite to other recommended research projects.

C. Development of Concrete Flow Control Devices for Tremie Systems

Flow of concrete mixtures out of tremie pipes is primarily controlled by the depth the tremie is submerged in the placed concrete and the concrete height in the tremie pipe. Flow control devices have been utilized downhole when placing oil well cements, but the devices are not capable of handling large size aggregates.

Research efforts should be directed toward development of flow control devices that can control the rate of concrete placement after the concrete has entered the placement system. The device could be a flow control device at the lower end of the discharge pipe that could be regulated from the surface. The control should provide complete shutoff to assist stopping and starting of placement without the need to clear the pipe and restart placement operations. Such device should be applicable for either open or closed tremie systems.

The work required would be a medium size research development project to extend the capability of current flow control devices to handle concrete mixture aggregates. This work would follow after the flow properties of concrete mixtures have been obtained and pertinent field tests for control purposes developed.

D. Development of Energy Dissipation Devices for Tremie Pipes

Energy dissipation devices in tremie pipes other than friction flow resistance need to be developed for both open and closed systems. The energy dissipation device would provide a uniform flow to the bottom of the tremie pipe regardless of the intermittent batch type of input to the delivery system. The device would also prevent the sudden emptying of the pipe if the bottom seal is lost due to pipe movement. There is no known mechanical tool technology which might be used with this project.

The energy dissipation device would be very dependent on the flow properties of the concrete mixtures. Development of the device would therefore follow flow research outlined above. Once the flow properties have been defined, the work would be a moderate size development project.

E. Improvement of Concrete Materials for Water Resistance Capabilities

The movement of concrete mixtures through water results in some degree of separation of the cement from the aggregates. The separation is detrimental to placement processes, volumes placed, form configuration and surface finishes. Therefore, research should be conducted to provide

more cohesive mixtures that would resist the separation of cement and aggregate in a water environment. Research in this area would reduce the high skill required in placement techniques necessary with present concrete mixtures. Moderate research efforts could produce some improvement, but to obtain major improvements would probably require extensive and high-risk research.

F. Delayed Setting Materials

Placement of large volumes of concrete at deep depths could be better controlled if setting of concrete mixtures did not occur until the mixture was in place. Some work has been done with oil well cements that are mixed with diesel oil and do not react with the cement, but only provide good pumpability of the cement to placement. After the cement is in place, water displaces the mixing liquid and setting occurs. The diesel oil material would not meet environmental standards; however, there may be others, such as emulsions, polymers or plastics, which could be acceptable. A moderate research effort could possibly produce this capability in concrete mixture. This research would involve a high risk for failure.

G. Development of Guidance Systems for Material Placement

The placement of large volumes of concrete at ocean depths greater than diver working depth will require some type of guidance system for placement of concrete and forms. The guidance system should also include some sort of observation system to determine if the forms are in place and intact. The system will also be needed to insure that the mixture placement system is in the proper relation to the forms for proper placement of the concrete. The surveillance system then can monitor job operations and progress to insure successful job performance.

Guidance and monitoring systems have been developed for re-entry of drill pipe into holes on the ocean floor. This equipment should be investigated for its adaption to guiding tremie pipes to concrete placement points required for underwater construction. This project would probably only require minimal development work for depths to 12,000 feet.

H. Bridging and Fast-Setting Mixtures

Forms or other containment structures placed under water may contain open joints that would need to be closed before placement of concrete mixture. A fast-setting material capable of sealing these openings would be desirable for the initial material. This work would be more of a development project, since some work has been done with grout materials to provide these capabilities. Primary use of these type grouts were to close large drift openings in abandoned mines where the work had to be performed remotely. Using existing technology to a great degree, this research effort should not be risky or require extensive costs.

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